UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 10

IN THE MATTER OF:	)	
	)	**COMPLAINANT'S REBUTTAL PREHEARING EXCHANGE**
Special Interest Auto Works, Inc. and Troy Peterson, an Individual	)	**Docket No. CWA-10-2013-0123**
Kent, WA	)	
Respondents.	)	

Pursuant to 40 C.F.R. § 22.19, and the Presiding Officer's Order of January 17, 2014, Complainant Environmental Protection Agency ("Complainant" or "EPA") submits its Rebuttal Prehearing Exchange. For purposes of this Rebuttal Prehearing Exchange, "Site" refers to the property located at 25923 78th Avenue South, Kent, WA, 98032 on which Respondents operate an auto salvage yard.

I. COMPLAINANT'S WITNESSES AND SUPPLEMENTAL BRIEF NARRATIVE SUMMARY OF EXPECTED TESTIMONY

Complainant provided a list of proposed fact and expert witnesses in Complainant's Initial Prehearing Exchange. Complainant has identified an additional witness:

Sandra Brozusky (fact witness): Ms. Brozusky has 6 years of experience as an Environmental Protection Specialist in the Inspection and Enforcement Management Unit in EPA Region 10's Seattle, Washington Office, where she specializes in multi-media inspections conducted under the Clean Water Act, NPDES and the Clean Air Act. She has conducted roughly 140 inspections during this time, of which approximately one-third included water sampling. Prior to the EPA, she had 2 years of experience as an inspector for the Northwest Clean Air Agency. Ms. Brozusky visited the Special Interest Site on two occasions. She will testify regarding her observations of the Site during the inspection, her activities related to the collection of water samples, the procedures for collecting samples and transmitting the samples to the laboratory, and the consistency of her sampling effort with generally accepted protocols for water sampling.

Additionally, Complainant wishes to supplement the brief narrative summary of the following witnesses. These supplemental summaries are responsive to Respondent's Prehearing Exchange.

1. **Ms. Laurie Mann** (fact witness): In addition to the matters described in the brief narrative summary of Ms. Mann's testimony as part of Complainant's Initial Prehearing Exchange, Ms. Mann will testify regarding the EPA approved water quality standards and designated uses for the Green River-Duwamish watershed, including the designation of salmonid spawning for that portion of the Green River adjacent to the Special Interest Site. Ms. Mann will also explain the CWA § 303(d) requirement to identify pollution sources, and to consider the cumulative impacts of multiple pollutant sources on impaired waters. Ms. Mann will describe what is known about the nature and extent of impaired waters in the Green River and Duwamish watershed, and will testify that all sources of metal contamination in the Green River need to be reduced in order to improve water quality in the Lower Duwamish River.

    Ms. Mann will further testify that Ecology's water quality standards are designed to protect the Green River for salmon migration and rearing and that just west of the Special Interest Site, Ecology's "use" designations for the Lower Green River expand to include the rearing of juvenile salmon, including salmon that are designated as "threatened" under the Endangered Species Act.

Ms. Mann will testify that the Lower Duwamish Waterway is located 20 miles downstream of the Site, and is identified as being impaired by over 60 different pollutants, including each of the pollutants detected at the Site. She will testify as to EPA's findings that the cumulative impact of pollution from the Green River, including metal contamination, is contributing to sediment and fish tissue impairments in the Lower Duwamish River.

2. **Mr. Burt Shephard** (expert witness): In addition to the matters described in the brief narrative summary of Mr. Shephard's testimony as part of Complainant's Initial Prehearing Exchange, Mr. Shephard will testify that both individual chemicals and chemical mixtures can adversely affect fish and other aquatic and aquatic-dependent species in both the immediate vicinity of and downstream from Special Interest Auto.

Mr. Shephard will testify that multiple types of contaminants, including metals, petroleum products, and other organic chemicals such as those found in antifreeze/engine coolants and air conditioning refrigerants can all be released from automobile wrecking facilities. All of these chemicals can be toxic to fish and other aquatic and aquatic-dependent species. EPA established and has maintained since 1981 an extensive database of chemical concentrations known to elicit toxicity to aquatic species. This database, called ECOTOX (www.epa.gov/ecotox) currently contains more than 400,000 test records covering 5,900 aquatic and terrestrial species and 8,400 chemicals, and includes references allowing the user to find the original publications from which the toxicity data were obtained. Based on the available toxicity information, Mr. Shephard will discuss the likelihood that contaminants released from the facility may have adverse effects on the survival, reproduction and growth of the aquatic and aquatic-dependent species present in the vicinity of Special Interest Auto Works. He will also discuss the process by which contaminant exposure and contaminant toxicity information are integrated to evaluate and identify contaminant effects on aquatic and aquatic dependent species.

Mr. Shephard will testify that metals such as those found in the sample taken at the facility can be toxic to fish, aquatic plants, and other aquatic life. He will also testify that metals associated with solid particulates can settle to bottom sediments of water bodies and destroy bottom-dwelling invertebrates, plants, or incubating fish eggs via chemical toxicity, physical toxicity, or a combination of both toxicity routes.

II. COMPLAINANT'S REBUTTAL DOCUMENTS AND EXHIBITS

CX – 39 Map of Potentiometric Surface in the Qva Aquifer and Water Levels in the Qal Aquifer South King County Groundwater Management Area (Department of Natural Resources, February 2000)

CX – 40 EPA Stormwater Phase II Final Rule Conditional No Exposure for Industrial Activity Fact Sheet (January 2000 – revised December 2005)

CX – 41 EPA ECO Update/Ground Water Forum Issue Paper – Evaluating Ground-Water/Surface-Water Transition Zones in Ecological Risk Assessments Report (July 2008)

CX – 42 EPA Guidance on the Development, Evaluation, and Application of Environmental Models Report (March 2009)

CX – 43 Effect of Urban Soil Compaction on Infiltration Rate (Journal of Soil and Water Conservation; May/June 2006; ProQuest Research Library pg. 117)

CX – 44 Excerpt from Soil and Water Physical Principles and Processes Book (Daniel Hillel)

CX – 45 EPA Generic Quality Assurance Project Plan for the Industrial Stormwater Inspections Report (November 2011)

CX – 46 Assessment of Current Water Quantity Conditions in the Green River Basin Report (Northwest Hydraulics Consultants, Inc. September 2005)

CX – 47 EPA Industrial Stormwater Fact Sheet Series Sector M: Automobile Salvage Yards (December 2006)

CX – 48 Photo (Specialty Interest Auto Works, Inc. April 2013)

CX – 49 Excerpt from Groundwater Hydrology Second Edition (David Keith Todd)

CX – 50 Ground Water and Surface Water - A Single Resource (U.S. Geological Survey Circular 1139 1998)

CX – 51 Ecology Economic Impact Analysis National Pollutant Discharge Elimination System (NPDES) Wastewater Discharge General Permit (May 2009)

CX – 52 Western Washington Hydrology Model Version 3.0 User Manual (August 2006)

CX – 53 Soil Science Society of America Proceedings Journal - Hydrologic and Morphologic Implications of Anisotropy and Infiltration in Soil Profile Development (1969)

CX – 54 Puget Sound Salmon Recovery Plan (January 2007)

CX – 55 Ecology Industrial Stormwater Gross Revenue Information (Fiscal Year 2013

CX – 56 Chain of Custody

CX - 57 Sampling Field Notes

III. COMPLAINANT'S REBUTTAL TO THE FACTUAL AND LEGAL BASIS FOR THE ALLEGATIONS DENIED AND FOR ASSERTED AFFIRMATIVE DEFENSES

The Prehearing Order requires Complainant to submit as part of its Rebuttal Prehearing Exchange "a statement and/or any documents in response to Respondent's Prehearing Exchange." Order, p. 4. Respondent's Prehearing Exchange presents its arguments related to the issues set forth below.

A. Respondents Were Required to Obtain Permit Coverage

Respondents claim they operated under the "reasonable belief" that all stormwater on the Site infiltrated vertically into groundwater and that no permit was required for discharges of stormwater into the Green River. The federal regulations in 40 C.F.R. §122.26(b)(14)(i)-(xi) identify eleven categories of stormwater discharges associated with industrial activity that are required to obtain coverage under an NPDES permit unless otherwise excluded. This means that, regardless of Respondents' belief with respect to a discharge, Respondents were required by law to obtain a permit by virtue of the fact that they fall within one of the specific industrial categories covered by stormwater regulations.

There is a conditional exclusion for discharges of stormwater associated with industrial activity if there is "no exposure" of industrial materials and activities to rain, snow, snowmelt and/or runoff and all industrial materials and activities are protected by a storm resistant shelter. 40 C.F.R. 122.26(g). "No exposure" means that all industrial materials and activities are protected by a storm resistant shelter to prevent exposure to rain, snow, snowmelt, and/or runoff. 40 C.F.R. 122.26(g). Industrial materials or activities include, but are not limited to, material handling equipment or activities, industrial machinery, raw materials, intermediate products, by-products, final products, or waste products. EPA will introduce testimony and evidence that Site conditions exposed stormwater to pollutants from industrial activities. Examples of the evidence Complainant will introduce to show that industrial activities and equipment were exposed to stormwater at the Site are EPA's inspection reports. These reports document EPA's observations that there were numerous oil and gas spills throughout the Site that were being carried via stormwater to ponded areas along the northern boundary of the Site, which is on the bank of the Green River and along the south west fence of the facility. There were pools of spilled antifreeze and transmission fluid on the ground and no pollution prevention measures were in place in the vicinity of the vehicle crusher. Containers of automobile fluids, oily car parts, radiators, and other parts were exposed to the elements. There were heavy petroleum fumes in the storage area/garage near the partially covered processing area. See, CX-05, CX-06. Under these conditions, industrial equipment and activities were fully exposed to the rain and other weather conditions. As a result, Respondents would not qualify for the "no exposure" exclusion for discharges of stormwater associated with industrial activity. In addition, there is no evidence that Respondents submitted a certification that there are no discharges of stormwater contaminated by exposure to industrial materials and activities from the entire facility.

Ample public information is readily available to auto salvage yard owners and operators of the regulatory requirements that apply to their industry. Given the public outreach conducted to educate auto salvage yards of their legal obligations with respect to stormwater, Respondents' erroneous belief that they were not required to apply for permit coverage was not reasonable. See, CX 40 and CX 47.

Finally, the regulatory provisions of the CWA were written without regard to intentionality, making the person responsible for the discharge of any pollutant strictly liable. 33 U.S.C. §1311. As stated by the Court in *U.S. v. Earth Sciences*, the CWA would be severely weakened if only intentional acts were proscribed. *U.S. v. Earth Sciences, Inc.*, 599 F.2d 368, 374 (1979). Therefore, Respondents' beliefs, whether reasonable or unreasonable, are irrelevant to its liability under the CWA.

B. Complainant's Hydrologic Modeling Accurately Represents Discharges from the Site

Respondents claim that Complainant's hydrological modeling does not accurately predict stormwater discharges from the Site. Respondents' Initial Prehearing Exchange, p. 14.

Complainant will provide evidence at trial through the testimony of Dr. Marshalonis and Mr. Beyerlein that use of hydrologic modeling to simulate stormwater runoff from sites such as Respondents' Site is widely accepted by the scientific community and is a reliable means of calculating predicted runoff events for a designated time period. Observations of Site conditions were used to corroborate the model's inputs and findings. Complainant's witnesses will demonstrate that the calibrations and assumptions used in the model are accurate and result in a scientifically sound and reasonably accurate assessment of the number of discharges of stormwater from the Site. Further, courts have upheld the use of hydrologic modeling as a basis for determining the number of discharges from facilities in stormwater cases. *See, In Re Leed Foundry, Inc.*, Docket No. CWA-03-2004-006 (April 24, 2007) (EPA's use of modeling to extrapolate multiple discharges accepted by the Court); *See also*, *In re Service Oil Co.*, Docket No. CWA-08-2005-0010 (August 3, 2007) (expert testimony regarding stormwater runoff from construction site that was based on computer modeling held to be reliable evidence of discharge).

C. Stormwater Discharges to the Green River

Respondents asserted that EPA "has no proof, based on physical evidence that stormwater emanating from the Site actually reached and flowed into the Green River." Respondents' Prehearing Exchange p. 10. Complainant will present testimony and evidence that the Site is located on the banks of the Green River, and that the Green River surrounds the Site on three sides. Complainant's experts will testify that basic principles of hydrology, as well as site-specific conditions support the conclusion, with scientific certainty, that stormwater flows directly to the Green River.

IV. SPECIFICATION OF PROPOSED PENALTY

A. CWA Penalty Assessment Authority

In accordance with Section 22.14 of the Part 22 Rules, 40 C.F.R. § 22.14(a)(4)(ii), the Complaint in this matter did not specify a penalty demand. Rather, Complainant decided to consider fully the information provided through the prehearing exchange process before proposing a specific penalty. Having done so, and in accordance with Section 22.19(a)(4) of the Part 22 Rules, 40 C.F.R. § 22.19(a)(4), and the Presiding Officer's Order of January 17, 2014, Complainant hereby proposes that Respondents be assessed a penalty of $177,500 for the violations identified in the Complaint.

CWA Section 309(g), 33 U.S.C. § 1319(g), authorizes the assessment of a Class II administrative civil penalty for a violation of CWA Section 301, 33 U.S.C. § 1311, up to $10,000 per day for each day the violation continues, with a maximum penalty of $125,000. Pursuant to the Debt Collection Improvement Act of 1996, 31 U.S.C. § 3701, the statutory maximum administrative penalty amounts have been increased to $11,000 per day, with a maximum penalty of $157,500. The Civil Monetary Penalty Inflation Adjustment Rule increased the administrative penalty from $11,000 per day of violation to $16,000 for violations occurring after January 12, 2009, Federal Register Volume 73 Number 239, pages 75340-75346, with a maximum penalty of $177,500. 40 C.F.R. § 19.4, Table 1.

B. Statutory Penalty Factors

The Consolidated Rules of Practice at 40 C.F.R. Part 22 require the Presiding Officer to assess a penalty based on the evidence in the record, the penalty criteria set forth in the relevant statute, and any civil penalty guidelines issued under the Act. The Act's statutory penalty criteria include:

> [T]he nature, circumstances, extent and gravity of the violation, or violations, and, with respect to the violator, ability to pay, any prior history of such violations, the degree of culpability, economic benefit or savings (if any) resulting from the violation, and such other matters as justice may require. 33 U.S.C. § 1319(g)(3).

There is no precise formula by which these factors must be computed. *In re Service Oil, Inc*., 2008 EPA App. LEXIS 35, 39 (ALJ 2008); *In re Larry Richner*, 10 E.A.D. 617 (EAB July 22, 2002); *In re Britton Construction*, 8 E.A.D. 261, 278 (EAB 1999). EPA has never issued a penalty policy for use by Presiding Officers in determining penalties under the Act. Consequently, Presiding Officers rely on the wording of the statutory penalty criteria provided above. The Supreme Court has indicated that highly discretionary calculations are necessary in assessing penalties under the Act. *Tull v. United States*, 481 U.S. 412, 427 (1987).

The evidence in this matter will show that between August 1, 2008 and October 4, 2012, Respondents discharged pollutants into the Green River on 989 days without coverage under the ISGP, in violation of CWA Section 301. Complainant's Initial Prehearing Exchange at pg 10; *see* CX – 05, 06, 07, and 30. Based on the applicable administrative maximum penalty per day of violation (i.e., $11,000 for violations occurring on or before January 12, 2009, and $16,000 for violations occurring after January 12, 2009), Respondents are liable for over $15 million. By virtue of the fact that EPA decided to pursue this matter administratively, rather than judicially, the penalty Complainant is seeking is capped at $177,500 - an amount that represents less than $180 per violation of the CWA.[1] Given the evidence to be presented at trial supporting Complainant's evaluation of the statutory penalty factors, this number underestimates the per

[1] It should be noted that had EPA elected to pursue this matter judicially rather than administratively, Respondents would have been subject to a statutory maximum civil penalty of more than $36 million. *See* 33 U.S.C. § 1319(d) (authorizing civil penalties "not to exceed $25,000 per day for each violation"); 40 C.F.R. § 19.4, Table 1 (adjusting the statutory maximum civil judicial penalty to $37,500).

violation value of the violations. It should be noted that had EPA elected to pursue this matter judicially rather than administratively, Respondents would have been subject to a statutory maximum civil penalty of more than $36 million. *See* 33 U.S.C. § 1319(d) (authorizing civil penalties "not to exceed $25,000 per day for each violation"); 40 C.F.R. § 19.4, Table 1 (adjusting the statutory maximum civil judicial penalty to $37,500).

The proposed penalty of $177,500 is based on CWA Section 309(g)(3), which identifies the statutory penalty factors applicable to this case. These factors are "[1] the nature, circumstances, extent, and gravity of the violation, or violations, and, with respect to the violator, [2] ability to pay, [3] any prior history of such violations, [4] the degree of culpability, [5] economic benefit or savings (if any) resulting from the violation, and [6] such other matters as justice may require." 33 U.S.C. § 1319(g)(3). The following discussion outlines the legal and factual framework employed in proposing this specific penalty amount, elaborates on the penalty discussion contained in Complainant's Initial Prehearing Information Exchange, and provides a rebuttal to issues raised in Respondents' Prehearing Exchange.

C. Nature, Circumstances, Extent, and Gravity of the Violation

The nature, circumstances, extent, and gravity of the violation reflect the "seriousness" of the violation. *See, In re Urban Drainage and Flood Control District, et al.*, Docket No. CWA-VIII-94-20-PII, 1998 EPA ALJ Lexis 42, at *56 (Initial Decision, June 24, 1998). The seriousness of a particular violation depends primarily on the actual or potential harm to the environment resulting from the violation, as well as the importance of the violated requirement to the regulatory scheme. *See id.*

The evidence in this matter indicates that the nature, circumstances, extent, and gravity of Respondents' violations are significant and justify a substantial penalty. Complainant's expert's hydrologic modeling demonstrates that hundreds of discharges of stormwater occurred over an extended period of time. Contrary to Respondents' contention that "[t]here is no evidence to support any claim that Respondents discharged stormwater to the Green River," Respondents' Prehearing Exchange at 18, Complainant has substantial evidence that Respondents discharged stormwater from industrial activities to the Green River over 900 times. *See In re Robert Wallin*, 10 E.A.D. 18, 32-33 (EAB 2001) (assessing the gravity of the violations and finding that circumstantial evidence in the record supports a conclusion that the Presiding Officer erred in finding it highly improbable that discharges from the respondent's dairy reached waters of the United States); *Concerned Area Residents for the Environment v. Southview Farm*, 34 F.3d 114 (2d. Cir. 1994) (holding that evidence of discharge to a navigable water from a point source may be proved by circumstantial evidence). Complainant's expert witnesses, Dr. Marshalonis and Mr. Beyerlein, will present scientific evidence that the facility's location on the bank of the Green River, the type of soil and industrial activities at the facility, site hydrology, topography, and the precipitation in the area combine to make it a scientific certainty that stormwater at the Site is flowing directly to the Green River.

In addition, analysis of stormwater samples taken during EPA's second inspection confirmed the presence of harmful pollutants that Respondents would have been required to monitor under the ISGP, including petroleum, zinc, copper, and lead. Sampling results show that ISGP benchmarks for copper, zinc, total petroleum hydrocarbon (TPH) were exceeded in the discharge leaving the Site during the second inspection. In addition, visible oil sheen was observed at the Site by EPA inspectors, which is also in violation of ISGP benchmarks. CX-25 – 27.

There is significant potential for environmental harm in this case, and Complainant need not prove actual harm to justify a substantial penalty. *See United States v. Municipal Authority of Union Township*, 929 F. Supp. 800, 807 (M.D. Pa. 1996) ("It must be emphasized, however, that because actual harm to the environment is by nature more difficult and sometimes impossible to demonstrate, it need not be proven to establish that substantial penalties are appropriate in a Clean Water Act case."), *aff'd* 150 F.3d 259 (3d Cir. 1998); *Urban Drainage,* 1998 EPA ALJ Lexis 42, at *65 ("A significant penalty may be imposed on the basis of potential environmental risk without necessarily demonstrating actual adverse effects") (citing *United States v. Smithfield Foods, Inc*. 972 F. Supp. 338, 344 (E.D. Va. 1997), *aff'd*, 191 F.3d 516 (4th Cir. 1999)); *United States v. Gulf Park Water Company, Inc.*, 14 F. Supp. 2d 854, 860 (S.D. Miss. 1998) ("The United States is not required to establish that environmental harm resulted from the defendants' discharges or that the public health has been impacted due to the discharges, in order for this Court to find the discharges 'serious'. . . . Under the law, the United States does not have the burden of quantifying the harm caused to the environment by the defendants").

The evidence in this matter will establish that the pollutants emanating from Respondents' Site enter sensitive receiving waters. As required by the Clean Water Act, the State of Washington has designated the uses of all rivers, streams, lakes and marine waters in Washington and has developed water quality standards that support those "uses." Designated uses for the Green River include boating, swimming, and protection of aquatic life, such as salmon.

Testimony from Ms. Mann will provide evidence that the Green River is natural habitat for salmon, including salmon that are identified by the Endangered Species Act as being "threatened". CX-54. She will testify that Ecology's water quality standards are designed to protect the Green River for salmon migration and rearing and that, just west of the Special Interest site, Ecology's "use" designations for the Lower Green River expand to include the rearing of juvenile salmon, including salmon that are designated as "threatened" under the Endangered Species Act. Evidence will be presented that the Lower Duwamish Waterway is located 20 miles downstream of the site, and is identified as being impaired by over 60 different pollutants, including each of the pollutants detected at the Site. Ms. Mann will testify as to EPA's findings that the cumulative impact of pollution from the Green River, including metal contamination, is contributing to sediment and fish tissue impairments in the Lower Duwamish River.

The Puget Sound Salmon Recovery Plan (draft 2005) includes a specific plan for restoring salmon to the Green – Duwamish watershed. CX-54. One of the salmon recovery projects recommended in the plan is the purchase and removal of the "auto wrecking yard" between river miles 24.3 and 25.1, which is the general location of Special Interest Auto Works, Inc, Site. CX-54 at pg. 7-61. Clearly this stretch of the Green River is important for salmon habitat and there are adverse environmental impacts associated with auto salvage operations.

Complainant will provide evidence that contaminants released from the facility may have adverse effects on the survival, reproduction and growth of the aquatic and aquatic-dependent species present in the vicinity of Special Interest Auto Works. Metals such as those found in the sample taken at the facility can be toxic to fish, aquatic plants, and other aquatic life. Metals associated with solid particulates can settle to bottom sediments of water bodies and destroy bottom-dwelling invertebrates, plants, or incubating fish eggs via chemical toxicity, physical toxicity, or a combination of both toxicity routes.

Any unpermitted discharge into waters of the United States is a serious violation which significantly undermines the CWA's regulatory scheme. *See United States v. Pozsgai,* 999 F.2d 719, 725 (3rd Cir. 1993) (noting that "[u]npermitted discharge is the archetypal Clean Water Act violation, and subjects the discharger to strict liability").

For all of these reasons, Complainant believes that the violations at issue in this case are serious and warrant a substantial civil penalty. Complainant believes the penalty proposed today would serve as a deterrent without being disproportionate to the seriousness of the violations.

D. Ability to Pay

In its 1994 *New Waterbury, Ltd.* decision, the Environmental Appeals Board ("EAB") set forth a now well-established process for considering and proving in the context of an administrative hearing a violator's ability to pay a civil penalty.

> Where ability to pay is at issue going into a hearing, the Region will need to present some evidence to show that it considered the respondent's ability to pay a penalty. The Region need not present any *specific* evidence to show that the respondent *can pay* or obtain funds to pay the assessed penalty, but can simply rely on some *general* financial information regarding the respondent's financial status which can support the *inference* that the penalty assessment need not be reduced. Once the respondent has presented *specific* evidence to show that despite its sales volume or apparent solvency it cannot pay any penalty, the Region as part of its burden of proof in demonstrating the "appropriateness" of the penalty must respond either with the introduction of additional evidence to rebut the respondent's claim or through cross examination it must discredit the respondent's contentions.

In re New Waterbury, Ltd., 5 E.A.D. 529, 542-430 (EAB 1994) (emphasis in original); *see also In re Chempace Corp.,* 9 E.A.D. 119, 132-33 (EAB 2000). Accordingly, while the Region has the initial burden of production to establish that the respondent has the ability to pay the proposed penalty, "[t]he burden of production then shifts to the respondent to establish with specific information that the proposed penalty assessment is excessive or incorrect." *Chempace*

Corp. at 133. Failure by a respondent to provide specific evidence substantiating a claimed inability to pay results in waiver of that claim. *In re Spitzer Great Lakes Ltd.,* 9 E.A.D. 302, 321 (EAB 2000).

In Respondents' Amended Answer, Affirmative Defenses and Request for Hearing, Respondents claimed that they do not have the ability to pay any civil penalties and that they were able to present information demonstrating an inability to pay a substantial penalty. Amended Answer at 11-13. In Complainant's Initial Prehearing Exchange, Complainant stated that it would consider any information regarding income, assets, debts, or liabilities in proposing a specific penalty amount. Complainant's Initial Prehearing Exchange at 12. Respondent reported gross revenue in the range of $1 million to $2.5 million to the Department of Ecology on the Industrial Stormwater Gross Revenue Information form for fiscal year 2013. CX-55. This information combined with the Respondents' tax returns provided in their prehearing exchange indicate that Respondents have the ability to pay a penalty. RX–8 and 9.

The proposed penalty does not include any reduction to reflect Respondents' claimed inability to pay, and Complainant believes that any downward adjustment based on this factor would be inappropriate at this time. Complainant will file a motion for additional discovery seeking the specific information Respondents may have that supports a claim of inability to pay. At any hearing in this matter, Complainant will demonstrate that it has considered Respondents' ability to pay in proposing a civil penalty and will, at a minimum, present general financial information about Respondents that shows that they are financially solvent.

E. Prior History of Violation

Complainant is unaware of Respondents having any prior history of violations of the CWA, and therefore has not increased or reduced the proposed penalty based on this factor.

F. Degree of Culpability

In other CWA enforcement cases, presiding officers have noted "the respondent's willful disregard of the permit process or Clean Water Act requirements" as supporting the assessment of the maximum penalty allowed by statute. *See, e.g., In re Urban Drainage*, Initial Decision (June 24, 1998). In this case, Respondents' disregard of CWA requirements is manifested in their failure to obtain a discharge permit over the course of several years. First, information is readily available to the public that sets forth permit requirements for the auto salvage industry. CX 47 and CX-40. Respondents were informed of permit requirements multiple times prior to the date on which they submitted a Notice of Intent to apply for permit coverage. In November of 2011 EPA conducted a broad outreach to auto salvage businesses in order to notify them of Washington Department of Ecology's permit requirements and the potential consequence to auto salvage yard operators if they failed to comply with such requirements. CX–04. Respondents deny receipt of EPA's mailing. However, even if Respondents did not receive the mailing, they had ample notification of the need to apply for a permit. Subsequent to EPA's broad outreach mailing, EPA communicated directly with Respondents during EPA's two inspections of the facility in March and February 2012 about the need to obtain permit coverage. EPA sent a Notice of Violation to Respondents in July, 2012. CX–05, 06. Despite these warnings, Respondents did not apply for permit coverage until October 4, 2012, over a year from the date EPA mailed information to Respondents informing them of permit requirements.[2] Even after Respondents obtained permit

2 There is some confusion over the exact date that Respondents applied for coverage under the ISGP. Complainant acknowledges Respondent's claim in its Prehearing Exchange that it applied for coverage under the ISGP in April of 2012. However, information in CX-09 indicates that Ecology did not receive the application for coverage until October 4, 2012. Further confusing the matter is the fact that Respondent's signature on the application is dated August 28, 2012. In any event, it is clear that Respondents did not immediately apply for coverage after EPA's inspections and notices.

coverage, on May 10, 2013, the Department of Ecology issued a warning of non-compliance to Respondents for failure to comply with the conditions of the permit. CX–11, 12.

G. Economic Benefit

Complainant believes that Respondents have realized an economic benefit as a result of the violations described above. Removing a violator's economic benefit is crucial in order to dampen incentives for noncompliance and eliminate any competitive advantage that the violator gains through its illegal activities. *See In re B.J. Carney Indus., Inc.*, 7 E.A.D. 171, 207-08 (EAB 1997), *appeal dismissed as untimely*, 192 F.3d 917 (9th Cir. 1999), *vacated pursuant to settlement*, 200 F.3d 1222 (2000). The exact economic benefit a polluter has gained by violating the CWA may be difficult to prove, so a reasonable approximation of the economic benefit is appropriate. *United States v. Smithfield Foods, Inc.*, 191 F.3d 516, 529 (4th Cir. 1999), *cert. denied*, 531 U.S. 813 (2000).

Generally, estimates of Respondents' delayed and avoided costs are based a non-compliance period beginning on August 1, 2008 (the first full month Respondents operated the Site) and ending on October 9, 2012 (the date Respondents received coverage under the ISGP). CX-09. In Respondents Prehearing Exchange, they argue that the evidence does not support an inference that Respondents have enjoyed an economic benefit over an extended period of time. Respondents' Prehearing Exchange at 23-24. In support, they cite *In re Robert Wallin*, 10 E.A.D. 18 (EAB 2001), a case in which the EAB issued a fine of $5,500 for a single alleged unauthorized discharge of pollutants into waters of the United States. In that case, the EAB would not infer based on a single, documented violation that the respondents were out of compliance over a much longer period of time, where the record did not contain evidence that discharges were likely to reach a navigable water during the extended time frame or that respondents were even subject to regulation under the CWA during the extended time frame. *Id.* at 24-25. Here, in contrast to *In re Robert Wallin*, Complainant has substantial evidence of Respondents' extended noncompliance, including two inspections and modeling data that shows over 900 days of discharges of stormwater offsite. *See* CX – 05, 06, and 30.

Respondents' economic benefit includes the delayed or avoided compliance costs associated with Respondents' failure to: 1) apply for, obtain and annually retain coverage under the applicable ISGP; 2) develop an adequate stormwater pollution prevention plan (SWPPP); 3) conduct inspections on a regular basis; and 4) conduct sampling of stormwater discharges offsite.

1. *Avoided Costs of Obtaining and Retaining ISGP Coverage*

Facilities conducting industrial activities that discharge stormwater to a water body are required to apply and obtain and retain coverage under the ISGP on an annual basis. The economic benefit for failing to obtain and retain coverage of the applicable ISGP was calculated as an avoided and recurring cost. For coverage under the ISGP, the Washington State Department of Ecology charged Respondents a fee of $1,157 for fiscal year 2014. This fee was based on the gross revenue reported by Special Interest Auto Works, Inc. of more than $2.5 million and less than $5 million.

The economic benefit was calculated as avoided recurring cost for failing to obtain and retain permit coverage using BEN version 5.4.0. (BEN). Using a non-compliance date of August 1, 2008 and a compliance date of October 9, 2012 (the date Respondent obtained coverage for the Site under the ISGP, the Respondent received an economic benefit of $4,074.

2. *Delayed Costs of Developing a SWPPP*

Under the ISGP, Respondents should have developed a SWPPP. A SWPPP must include: a detailed description of the BMPs necessary to prevent, control, and treat stormwater pollution, and prevent a violation of water quality standards; proper selection and use of stormwater management manuals; a site map; a detailed assessment of the facility, including activities and equipment that contribute or have the potential to contribute pollution to stormwater; identification of a pollution prevention team; and a sampling plan. Based on typical costs for SWPPP development in the automobile salvage sector and Respondents' invoices for preparation of SWPPP, RX-10, the total estimated cost for preparing a SWPPP is $5,000.

The economic benefit derived from this cost is calculated using EPA's economic model, BEN version 5.4.0. (BEN) as a *delayed one-time, non-depreciable cost*, as Respondents have received coverage under the ISGP and prepared a SWPPP for the Site. Using a non-compliance date of August 1, 2008, and compliance date of October 9, 2012, Respondent received an economic benefit for delaying preparation of a SWPPP of $1,578.

3. *Avoided Costs of Conducting Visual Inspections*

Under the ISGP, the Respondents should have conducted and documented visual inspections of the Site each month. Based on conditions of the Site, EPA estimates that visual inspections of the Site will take approximately one half hour. Using Ecology's *Economic Impact Analysis, NPDES Wastewater Discharge General Permit: Industrial Stormwater General Permit*, Table 10 (May 2009) (hereinafter "*Economic Impact Analysis for the ISGP*"), the estimated costs for visual inspections is $564.

The economic benefit for the avoided inspections and inspection reports is calculated using BEN version 5.4.0 as an avoided recurring cost. The non-compliance date used in BEN is August 1, 2008, and the date of compliance will be October 9, 2012. The economic benefit received by the Respondents for avoided cost of conducting inspections of the Site is $537.

4. *Avoided Costs of Conducting Stormwater Sampling*

Under the ISGP, the Respondents should have conducted quarterly sampling of their stormwater discharges offsite. Specifically, Respondents are engaged in automobile salvage and scrap recycling (SIC 5015 to 5093), should have sampled stormwater discharges for turbidity, pH, oil sheen, copper, zinc, lead, and total petroleum hydrocarbons. Costs associated with quarterly sampling include sample collections and recording keeping. For purposes of calculating these costs, EPA assumed Respondents' staff would conduct the sample collection. Using Ecology's *Economic Impact Analysis of the ISGP*, Table 7, the estimated cost for sample collections and recording keeping is $1,900. Additionally, there are costs associated with sample analysis, including laboratory fees and sampling equipment (e.g., pH sampling equipment, which is conducted on site). Using sampling costs from EPA's Manchester Laboratory in Port Orchard, Washington, the estimated cost for sample analysis is $3,213.

The economic benefit for the avoided stormwater sampling is calculated using BEN version 5.4.0. as an avoided recurring cost. The non-compliance date used in BEN is August 1, 2008, and the date of compliance will be October 9, 2012. The economic benefit received by the Respondents for avoided cost of conducting sampling of the Site is $4,433.

Total Economic Benefit

Based on the available information, the economic benefit associated with Respondents' failure to apply for, obtain and retain coverage under the ISGP, develop a SWPPP, conduct monthly visual inspections, and conduct quarterly stormwater sampling is $10,622.

H. Other Matters as Justice May Require

After reviewing information in Respondents' Prehearing Exchange, Complainant does not believe there are facts in this matter that would dictate a reduction the proposed penalty based on this factor.

USEPA REGION 10
1200 SIXTH AVE, SUITE 900
ORC-158
SEATTLE, WASHINGTON 98101

For all of the foregoing reasons, Complainant proposes that Respondents be assessed a civil penalty of $177,500. Such a penalty would be appropriate and would properly reflect the considerations enumerated in Section 309(g) of the CWA.

V. REBUTTAL TO REQUEST FOR DISCOVERY

Respondents have requested additional discovery in order to obtain specific documents related to sampling and to depose four of EPA's expert witnesses. The Consolidated Rules of Practice Governing the Administrative Assessment of Civil Penalties (Part 22 regulations), 40 C.F.R. 22.19(e)(1), require a party seeking additional discovery beyond the prehearing exchange to file a motion seeking such additional discovery. Despite the fact that Respondents have not filed a motion, Complainant responds to the request for discovery as follows. First, Complainant has included in this rebuttal prehearing exchange field notes (CX-57), chain of custody forms (CX-56), testing results (CX-07), and the Quality Assurance Project Plan (CX-45) in response to Respondents' discovery request. Complainant's expert witness, Ms. Sandra Brozusky, will testify as to the field sample techniques used.

Complainant objects to the request to depose Mr. Beyerlein, Ms. Mann, Mr. Shephard, and Mr. Oatis. The preamble to the Part 22 regulations evaluates the principles on which the prehearing exchange procedures are based in administrative practice and determines that the administrative practice is specifically designed to be a more streamlined process that the judicial process, in which large expenditures of resources are invested in a lengthy discovery process which typically includes depositions. Under the Part 22 regulations, other discovery has always been limited in comparison to the extensive and time-consuming discovery typical in the Federal courts, and designed to discourage dilatory tactics and unnecessary and time consuming motion practice. 64 Fed. Reg. 40138, 40160 (July 23, 1999).

Complainant specifically chose to pursue this matter administratively, rather than judicially, because administrative actions are more efficient, Agency resources are particularly limited at this time, and the Agency is mindful of burdening a small business such as Special Interest Auto Works, Inc. with the time and expense involved in a judicial proceeding. Granting a motion to conduct depositions places far more of a burden on both parties in the evidentiary process.

Pursuant to 40 C.F.R. §22.19(e), additional discovery may only be granted by the Presiding Officer if such discovery: (i) Will neither unreasonably delay the proceeding nor unreasonably burden the non-moving party; (ii) Seeks information that is most reasonably obtained from the non-moving party, and which the non-moving party has refused to provide voluntarily; and (iii) Seeks information that has significant probative value on a disputed issue of material fact relevant to liability or the relief sought. As discussed in the previous paragraph, Complainant believes that the request for depositions will unreasonably delay the proceedings and burden Complainant. With respect to the second criteria, Complainant has voluntarily augmented the summary of Ms. Mann's and Mr. Shephard's expert testimony in this Rebuttal Prehearing Exchange in order to provide additional detail about the expected testimony of its witnesses. Complainant firmly believes that the narrative summaries of its witnesses' expected testimony combined with the supporting evidence in this Rebuttal Prehearing Exchange and its Initial Prehearing Exchange are sufficient and that no further discovery is needed.

RESPECTFULLY SUBMITTED this 4th day of April, 2014.

/s/

Elizabeth McKenna
Assistant Regional Counsel
(206) 553-0016
mckenna.elizabeth@epa.gov

Certificate of Service

The undersigned certifies that the attached **Complainant's Rebuttal Prehearing Exchange**, dated April 7, 2014, In the Matter of Special Interest Auto Works, Inc. and Troy Peterson, Docket No. CWA-10-2013-0123, was filed with the Office of Administrative Law Judges and Respondents' counsel, Dennis Reynolds, Esq. via email at the following email addresses:

Sybil Anderson, EPA Headquarters Hearing Clerk: OALJfiling@epa.gov

Dennis Reynolds, Esquire: dennis@ddrlaw.com

DATED this 4th Day of April, 2014.

_______/s/____________

Elizabeth McKenna
Assistant Regional Counsel

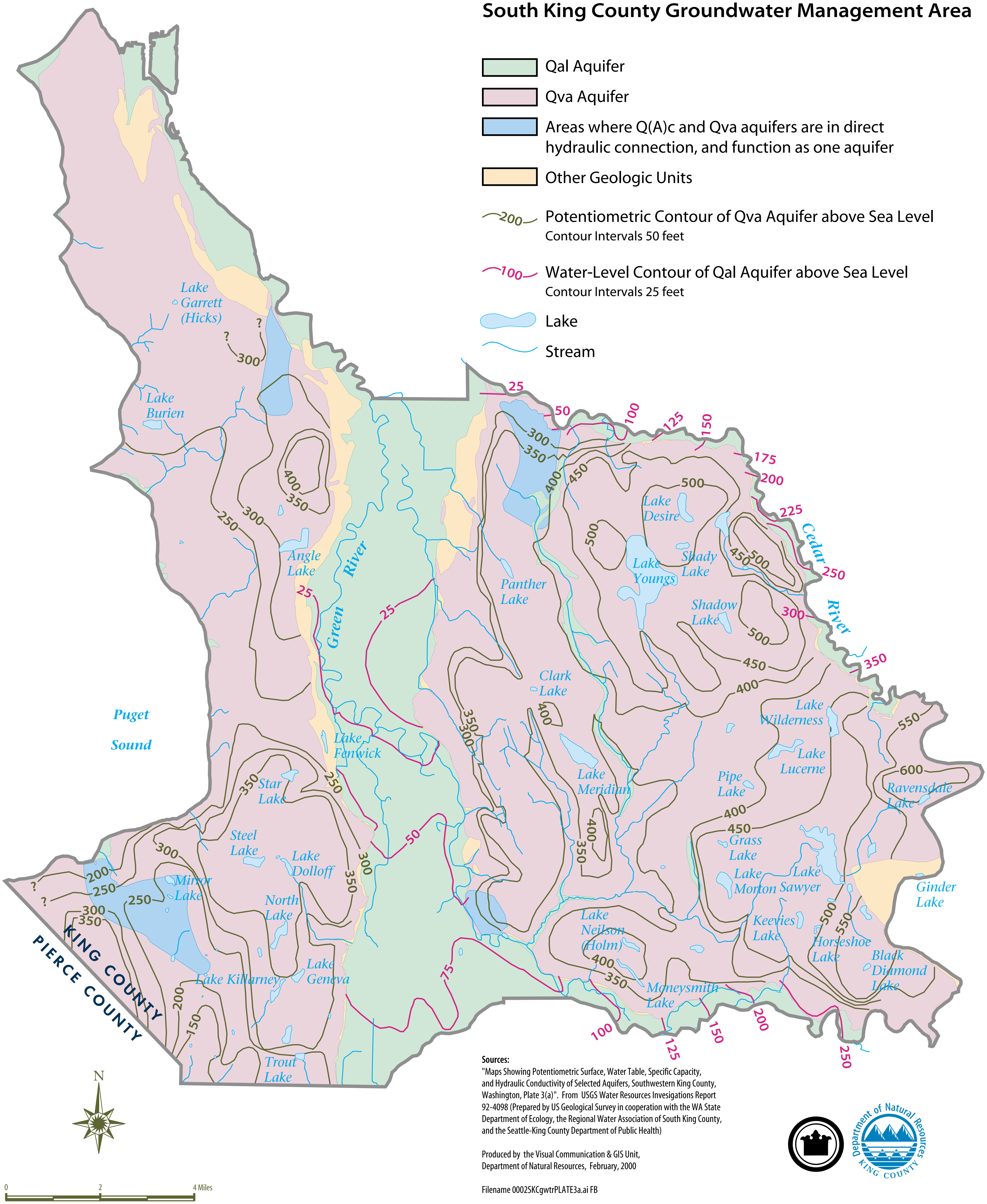
COMPLAINANT'S EXHIBIT 39

Potentiometric Surface

in the Qva Aquifer and Water Levels in the Qal Aquifer

South King County Groundwater Management Area

- Qal Aquifer
- Qva Aquifer
- Areas where Q(A)c and Qva aquifers are in direct hydraulic connection, and function as one aquifer
- Other Geologic Units
- 200 — Potentiometric Contour of Qva Aquifer above Sea Level
  Contour Intervals 50 feet
- 100 — Water-Level Contour of Qal Aquifer above Sea Level
  Contour Intervals 25 feet
- Lake
- Stream



Sources:
"Maps Showing Potentiometric Surface, Water Table, Specific Capacity, and Hydraulic Conductivity of Selected Aquifers, Southwestern King County, Washington, Plate 3(a)". From USGS Water Resources Invesigations Report 92-4098 (Prepared by US Geological Survey in cooperation with the WA State Department of Ecology, the Regional Water Association of South King County, and the Seattle-King County Department of Public Health)

Produced by the Visual Communication & GIS Unit, Department of Natural Resources, February, 2000

Filename 0002SKCgwtrPLATE3a.ai FB

Department of Natural Resources
KING COUNTY

COMPLAINANT'S EXHIBIT 40

United States Environmental Protection Agency
Office of Water (4203)
EPA 833-F-00-015
January 2000 (revised December 2005)
Fact Sheet 4.0

EPA

Stormwater Phase II Final Rule

Conditional No Exposure Exclusion for Industrial Activity

Why Is the Phase I No Exposure Exclusion Addressed in the Phase II Final Rule?

The 1990 stormwater regulations for Phase I of the Federal stormwater program identify eleven categories of industrial activities that must obtain a National Pollutant Discharge Elimination System (NPDES) permit. Operators of certain facilities within category eleven (xi), commonly referred to as "light industry," were exempted from the definition of "stormwater discharge associated with industrial activity," and the subsequent requirement to obtain an NPDES permit, provided their industrial materials or activities were not "exposed" to stormwater. This Phase I exemption from permitting was limited to those facilities identified in category (xi), and did not require category (xi) facility operators to submit any information supporting their no exposure claim.

In 1992, the Ninth Circuit court remanded to EPA for further rulemaking the no exposure exemption for light industry after making a determination that the exemption was arbitrary and capricious for two reasons. First, the court found that EPA had not established a record to support its assumption that light industrial activity that is not exposed to stormwater (as opposed to all other regulated industrial activity not exposed) is not a "stormwater discharge associated with industrial activity." Second, the court concluded that the exemption impermissibly relied on the unsubstantiated judgment of the light industrial facility operator to determine the applicability of the exemption. These findings resulted in a revised conditional no exposure exclusion, the changes to which are described in this fact sheet.

Who is Eligible to Claim No Exposure?

As revised in the Phase II Final Rule, the conditional no exposure exclusion applies to ALL industrial categories listed in the 1990 stormwater regulations, except for construction activities disturbing 5 or more acres (category (x)).

What Is The Regulatory Definition of "No Exposure"?

The intent of the no exposure provision is to provide facilities with industrial materials and activities that are entirely sheltered from stormwater a simplified way of complying with the stormwater permitting provisions of the Clean Water Act (CWA). This includes facilities that are located within a larger office building, or facilities at which the only items permanently exposed to precipitation are roofs, parking lots, vegetated areas, and other non-industrial areas or activities. The Phase II regulatory definition of "no exposure" follows.

> ***No exposure*** is defined as all industrial materials and activities are protected by a storm resistant shelter to prevent exposure to rain, snow, snowmelt, and/or runoff. Industrial materials or activities include, but are not limited to, material handling equipment or activities, industrial machinery, raw materials, intermediate products, by-products, final products, or waste products.

A storm-resistant shelter is not required for the following industrial materials and activities:

- ❑ Drums, barrels, tanks, and similar containers that are tightly sealed, provided those containers are not deteriorated and do not leak. "Sealed" means banded or otherwise secured and without operational taps or valves;

- ❑ Adequately maintained vehicles used in materials handling; and

- ❑ Final products, other than products that would be mobilized in stormwater discharges (e.g., rock salt).

The term "storm-resistant shelter," as used in the no exposure definition, includes completely roofed and walled buildings or structures, as well as structures with only a top cover but no side coverings, provided material under the structure is not otherwise subject to any run-on and subsequent runoff of stormwater. While the intent of the no exposure provision is to promote a condition of permanent no exposure, EPA understands certain vehicles could become temporarily exposed to rain and snow while passing between buildings. Adequately maintained mobile equipment (e.g., trucks, automobiles, forklifts, trailers, or other such general purpose vehicles found at the industrial site that are not industrial machinery, and that are not leaking contaminants or are not otherwise a source of industrial pollutants) can be exposed to precipitation or runoff. Such activities alone would not prevent a facility from certifying to no exposure. Similarly, trucks or other vehicles awaiting maintenance at vehicle maintenance facilities that are not leaking contaminants or are not otherwise a source of industrial pollutants, are not considered "exposed."

In addition, EPA recognizes that there are circumstances where permanent no exposure of industrial activities or materials is not possible and, therefore, under such conditions, materials and activities can be sheltered with temporary covers (e.g., tarps) between periods of permanent enclosure. The no exposure provision does not specify every such situation, but NPDES permitting authorities can address this issue on a case-by-case basis.

The Phase II Final Rule also addresses particulate matter emissions from roof stacks/vents that are regulated by, and in compliance with, other environmental protection programs (i.e., air quality control programs) and that do not cause stormwater contamination are considered not exposed. Particulate matter or visible deposits of residuals from roof stacks and/or vents not otherwise regulated (i.e., under an air quality control program) and evident in stormwater outflow are considered exposed. Likewise, visible "track out" (i.e., pollutants carried on the tires of vehicles) or windblown raw materials is considered exposed. Leaking pipes containing contaminants exposed to stormwater are deemed exposed, as are past sources of stormwater contamination that remain onsite. General refuse and trash, not of an industrial nature, is not considered exposed as long as the container is completely covered and nothing can drain out holes in the bottom, or is lost in loading onto a garbage truck. Industrial refuse and trash that is left uncovered, however, is considered exposed.

What is Required Under the No Exposure Provision?

The Phase II Final Rule represents a significant expansion in the scope of the original no exposure provision in terms of eligibility (as noted above) and responsibilities for facilities claiming the exclusion. Under the original no exposure provision, a light industry operator was expected to make an independent determination of whether there was "exposure" of industrial materials and activities to stormwater and, if not, simply not submit a permit application. An operator seeking to qualify for the revised conditional no exposure exclusion, including light industry operators (i.e., category (xi) facilities), must:

- ❑ Submit written certification that the facility meets the definition of "no exposure" to the NPDES permitting authority once every 5 years.

  - The Phase II Final Rule includes a four-page *No Exposure Certification* form that uses a series of yes/no questions to aid facility operators in determining whether they have a condition of no exposure. It also serves as the necessary certification of no exposure provided the operator is able to answer all the questions in the negative. EPA's *Certification* is for use only by operators of industrial activity located in areas where EPA is the NPDES permitting authority.

  - A copy of the *Certification* can be obtained from the EPA stormwater Web site (http://www.epa.gov/npdes/stormwater), the Stormwater Phase II Final Rule published in the *Federal Register* (Appendix 4), or by contacting the appropriate NPDES permitting authority.

- ❑ Submit a copy, upon request, of the *Certification* to the municipality in which the facility is located.

- ❑ Allow the NPDES permitting authority or, if discharging into a municipal separate storm sewer system, the operator of the system, to: (1) inspect the facility; and (2) make such inspection reports publicly available upon request.

Regulated industrial operators need to either apply for a permit or submit a no exposure certification form to be in compliance with the NPDES stormwater regulations. Any permit held becomes null and void once a certification form is submitted.

Even when an industrial operator certifies to no exposure, the NPDES permitting authority still retains the authority to require the operator to apply for an individual or general permit if the NPDES permitting authority has determined that the discharge is contributing to the violation of, or interfering with the attainment or maintenance of, water quality standards, including designated uses.

Are There Any Concerns Related to Water Quality Standards?

Yes. An operator certifying that its facility qualifies for the conditional no exposure exclusion may, nonetheless, be required by the NPDES permitting authority to obtain permit authorization. Such a requirement would follow the permitting authority's determination that the discharge causes, has a reasonable potential to cause, or contributes to a violation of an applicable water quality standard, including designated uses. Designated uses can include use as a drinking water supply or for recreational purposes.

Many efforts to achieve no exposure can employ simple good housekeeping and contaminant cleanup activities such as moving materials and activities indoors into existing buildings or structures. In limited cases, however, industrial operators may make major changes at a site to achieve no exposure. These efforts may include constructing a new building or cover to eliminate exposure or constructing structures to prevent run-on and stormwater contact with industrial materials and activities. Major changes undertaken to achieve no exposure, however, can increase the impervious area of the site, such as when a building with a smooth roof is placed in a formerly vegetated area. Increased impervious area can lead to an increase in the volume and velocity of stormwater runoff, which, in turn, can result in a higher concentration of pollutants in the discharge, since fewer pollutants are naturally filtered out.

The concern of increased impervious area is addressed in one of the questions on the *Certification* form, which asks, "Have you paved or roofed over a formerly exposed, pervious area in order to qualify for the no exposure exclusion? If yes, please indicate approximately how much area was paved or roofed over." This question has no affect on an operator's eligibility for the exclusion. It is intended only to aid the NPDES permitting authority in assessing the likelihood of such actions interfering with water quality standards. Where this is a concern, the facility operator and its NPDES permitting authority should take appropriate actions to ensure that water quality standards can be achieved.

What Happens if the Condition of No Exposure Is Not Maintained?

Under the Phase II Final Rule, the no exposure exclusion is conditional and not an outright exemption. Therefore, if there is a change in circumstances that causes exposure of industrial activities or materials to stormwater, the operator is required to comply immediately with all the requirements of the NPDES Stormwater Program, including applying for and obtaining a permit.

Failure to maintain the condition of no exposure or obtain coverage under an NPDES stormwater permit can lead to the unauthorized discharge of pollutants to waters of the United States, resulting in penalties under the CWA. Where a facility operator determines that exposure is likely to occur in the future due to some anticipated change at the facility, the operator should submit an application and acquire stormwater permit coverage prior to the exposed discharge to avoid such penalties.

For Additional Information

Contacts

☞ U.S. EPA Office of Wastewater Management
http://www.epa.gov/npdes/stormwater
Phone: 202-564-9545

☞ Your NPDES Permitting Authority. Most States and Territories are authorized to administer the NPDES Program, except the following, for which EPA is the permitting authority:

Alaska	Guam
District of Columbia	Johnston Atoll
Idaho	Midway and Wake Islands
Massachusetts	Northern Mariana Islands
New Hampshire	Puerto Rico
New Mexico	Trust Territories
American Samoa	

☞ A list of names and telephone numbers for each EPA Region and State is located at http://www.epa.gov/npdes/stormwater (click on "Contacts").

Reference Documents

☞ EPA's Stormwater Web Site
http://www.epa.gov/npdes/stormwater
- Stormwater Phase II Final Rule Fact Sheet Series
- Stormwater Phase II Final Rule (64 *FR* 68722)
- National Menu of Best Management Practices for Stormwater Phase II
- Measurable Goals Guidance for Phase II Small MS4s
- Stormwater Case Studies
- And many others

COMPLAINANT'S EXHIBIT 41

United States Environmental Protection Agency
Office of Solid Waste and Emergency Response
Publication 9285.6-17
EPA-540-R-06-072
July 2008

ECO Update/ Ground Water Forum Issue Paper

Intermittent Bulletin

Evaluating Ground-Water/Surface-Water Transition Zones in Ecological Risk Assessments

Joint Document of the Ecological Risk Assessment Forum and the Ground Water Forum

IN THIS BULLETIN

The ECO Update Bulletin series provides technical information and practices to EPA Regions and States on specific components of the ecological risk assessment process at Superfund sites and RCRA Corrective Action facilities. This document does not substitute for CERCLA, RCRA, or EPA regulations, nor is it a regulation. Thus, it cannot impose legally binding requirements on EPA, the States, or the regulated community and may not apply to a particular situation based on the circumstances. The Ecological Risk Assessment Forum and Ground Water Forum identify and resolve scientific and technical issues related to risk assessments and remediation of Superfund and RCRA sites. The Forums are supported by and/or advise OSWER's Technical Support Centers and provide state-of-the-science technical assistance to EPA project managers.

TABLES

FIGURES

TEXT BOXES

1. Introduction

1.1 Purpose of This Joint ECO Update/ Ground Water Forum Issue Paper

Currently, there is a common perception that the discharge of contaminated ground-water to a surface-water body does not pose an ecological risk if contaminant concentrations in surface-water samples are below analytical detection limits or at very low concentrations. The transition zone represents a unique and important ecosystem that exists between surface-water and the underlying ground-water, receiving water from both of these sources. Biota inhabiting, or otherwise dependent on, the transition zone may be adversely impacted by contaminated ground-water discharging through the transition zone into overlying surface-waters. Ecological Risk Assessments (ERA) addressing contaminated ground-water discharge to surface-waters typically have not evaluated potential contaminant effects to biota in the transition zone. However, numerous hydrogeological and ecological methods and tools are available for delineating ground-water discharge areas in a rapid and cost-effective manner, and for evaluating the effects of contaminant exposure on transition zone biota. These tools and approaches, which are commonly used in hydrogeological and ecological investigations, can be readily employed within the existing EPA framework for conducting screening- and baseline-level ERAs in Superfund (U.S. EPA 1997) to identify and characterize the current and potential threats to the environment from a hazardous substance release.

This document was initially prepared as an ECO Update/Ground Water Forum Issue Paper to highlight the need to treat the discharge of ground-water to surface-water not as a two-dimensional area with static boundary conditions, but as three-dimensional volumes with dynamic transition zones. This ECO Update applies equally to recharge zones and can be used to evaluate advancing plumes that have not yet reached the transition zone. This document encourages project managers, ecological risk assessors, and hydrogeologists to expand their focus beyond shoreline wells and surface sediments and define and characterize the actual fate of contaminants as they move from a strictly ground-water environment (i.e., the commonly used "upland monitoring well nearest the shoreline") through the transition zone and into a wholly surface-water environment. The approach is presented to help users identify and evaluate potential exposures and effects to relevant ecological receptors within the zone where ground-water and surface-water mix. The transition zone data collected for the ERA may also supplement data collected for the evaluation of potential human health risks associated with the discharge of contaminated ground-water. Should ground-water remediation be warranted (as a result of the risk assessment), the locational, geochemical, and biological aspects of the transition zone can be considered when identifying and evaluating remedial options.

This ECO Update builds on the standard approach to ERA (U.S. EPA 1997), by providing a framework for incorporating ground-water/surface-water (GW/SW) interactions into existing ERAs (see U.S. EPA 1997 and 2001a for an introduction to ecological risk assessment). The purpose of the ERA within the risk assessment process is to:

a. Identify and characterize the current and potential threats to the environment from a hazardous substance release;
b. Evaluate the ecological impacts of alternative remediation strategies; and
c. Establish cleanup levels in the selected remedy that will protect those natural resources at risk (U.S. EPA 1994a).

This ECO Update focuses on the first of these by illustrating how one might consider GW/SW interactions when designing and conducting an ERA, both in terms of characterizing the physicochemical environment of the transition zone and evaluating potential ecological risks that may be incurred by receptors in the transition zone. The discharge of contaminated ground-water to a surface-water body through the underlying sediments is the principal focus of the document but other sources of ground-water contamination are also included that may be contributing potential risks to the biota of the transition zone and the overlying surface-waters (e.g., ground-water moving through contaminated sediment, NAPL discharge to sediment or surface-water, the role of downward vertical gradients). This document also identifies a suite of tools that can be used by all members of a site team (especially ecologists and hydrogeologists) to (1) determine the locations of contaminated ground-water discharging to surface-water; (2) estimate exposure point concentrations at these areas for use in evaluating potential ecological risks; and (3) evaluate actual and/or potential ecological effects of contaminants as they discharge to surface-water. Throughout this document, ecological resources means habitats, species, populations, and communities that occur at or utilize the ground-water discharge areas and the associated transition zones, sediments, and surface-waters, as well as the ecological functions of these entities (e.g., productivity, benthic respiration, biodegradation).

1.2 The Ground-Water/Surface-Water Transition Zone

1.2.1 Definition of the Transition Zone

The GW/SW transition zone represents a region beneath the bottom of a surface-water body where conditions change from a ground-water dominated to surface-water dominated system within the substrate. It is a region that includes both the interface between ground-water and surface-water as well as the broader region in the substrate (and, on occasion, up into the surface-water body) where ground-water and surface-water mix. Transition zones occur in stream, river, estuarine, marine, lake, and wetland settings, and may include the mixing of cold and warm waters, fresh and marine waters, or waters having other physical or chemical differences. The transition zone is not only an area where surface and ground-water mix, but also an ecologically active area beneath the sediment/water interface where a variety of important ecological and physicochemical conditions and processes may occur. Transition zones beneath streams and rivers may be termed hyporheic zones (White 1993) and those beneath lakes and wetlands termed hypolentic zones. A new discipline that studies ground-water relationships to surficial ecological systems is referred to as "ecohydrology" (Wassen and Grootjans, 1996) and has been the subject of recent study (Hayashi and Rosenberry 2002).

The existing and potential ecological effects of contaminated ground-water in the transition zone can be important considerations in site characterization and ecological risk assessment. In the past, ground-water and surface-water were typically viewed as separate compartments of an aquatic ecosystem, connected at the sediment/surface-water boundary. This paradigm ignored (1) the ecosystem that occurs within the transition zone, (2) the important geochemical and biological roles this zone may have in the local ecosystem (i.e., Gibert et al. 1994), and (3) the dynamic nature of this zone that results from the highly variable flow conditions in ground-water and surface-water. The new paradigm in this ECO Update/Issue Paper explicitly includes consideration of the transition zone as a vital habitat that is interconnected with, and supports the surface-water ecosystem (Valiela et al. 1990; Williams 1999).

1.2.2 Spatial and Temporal Variations of Transition Zones

The locations and characteristics of transition zones and associated ground-water discharge areas vary both spatially and temporally. These spatial and temporal variations will affect the occurrence and distribution of habitats dependent on ground-water discharge, and influence the ecological roles that the transition zone may have in maintaining local biotic communities. Not all areas of a surface-water body receive ground-water discharge.

The spatial distribution and the rate and direction of water flow within transition zones will be influenced by the type of water body into which the discharge is occurring, the elevation of surface-water relative to that of ground-water, and the underlying geological conditions. The rate of ground-water discharge may vary among the multiple discharges in direct response to hydraulic conditions and the varied geological characteristics in the discharge areas (Fetter 2000; Winter 1998). When there are large variations within a transition zone, a few preferential discharge areas may account for the majority of the discharge. Ground-water discharge rates also may vary temporally at individual discharge areas, reflecting seasonal changes in hydrogeologic conditions. Precipitation events, surface-water releases at dams or locks, and tidal fluctuations (including the reversal of water flow in the transition zone) also affect the rate of ground-water discharge to surface-water (Tobias et al. 2001).

1.2.3 Ecological Role of the Transition Zone

The understanding of the role that transition zones have in ecosystems directly influenced by ground-water discharges is increasing (Danielopol et al, 2003). Benthic and epibenthic communities (particularly invertebrate larvae, worms, bivalves, and fish) are major components of the transition zone ecosystem and many of these organisms spend part or all of their life cycle in contact with the sediments and ground-water that comprise this zone. These communities are well-known, valued for their ecological roles, and commonly assessed in ERAs. Typically, ERAs evaluate the effects of contaminated sediments on these benthic and epibenthic organisms because they are linked to upper-level trophic organisms via the food chain. However, as discussed in the examples below, other ground-water-influenced habitats within the transition zone as well as other transition zone organisms are ecologically important and therefore may appropriately be considered in the ERA. This document provides a framework to allow an ERA to better evaluate the existing and potential effects of contaminated ground-water on benthic ecosystems.

Although water may flow in either direction in a transition zone (i.e., both ground-water discharge to surface-water and surface-water recharge to ground-water), the transport of contaminants by ground-water discharging to surface-water is the subject of this document. In some aquatic systems, areas of ground-water discharge provide important habitats for a variety of aquatic biota and create thermal refugia for fish by supplying cooler, well-oxygenated waters during summer months or maintaining ice-free habitats in colder climate streams (Power et al. 1999).

Areas of ground-water discharge can create conditions capable of supporting spawning, feeding, and nursery habitats (Dahm and Valett 1996). For example, Geist and Dauble (1998) showed how nest site selection by salmonids is strongly influenced by the location of ground-water discharge zones in streams and estuaries. Ground-water discharge areas in streams may also provide important refugia for fish and invertebrates during the dry phase of intermittent streams and during stream flood events (Stanford and Ward 1993; Power et al. 1999). Algal community structure and recovery following disturbance have been shown to be influenced by ground-water discharge to the surface-water (Grimm 1996). Because of the important ecological role of the ground-water discharge areas, the discharge of contaminated ground-water may result in adverse ecological impacts to biota utilizing those areas (Carls et al, 2003).

In addition to the habitats at the sediment/surface-water interface, transition zones in these discharge areas have been shown to provide direct habitat for a variety of insect and fish larvae (Hayashi and Rosenberry 2002). For example, studies of freshwater hyporheic ecosystems have shown that some invertebrates utilizing the transition zone as a refuge may descend meters into the transition zone on a daily or seasonal basis.

Furthermore, a healthy, diverse flora and fauna in the transition zone is beneficial to basic aquatic ecosystem functioning. The wide array of organisms within the transition zone are critical to nutrient, carbon, and energy cycling in aquatic food webs (Storey et al., 1999; Hayashi and Rosenberry 2002). For example, up to 65 % of invertebrate production in a sandy stream was reported to occur in the hyporheic zone (Smock, et al. 1992; Boulton 2000). The thickness of the transition zone directly affects the amount of habitat available for these organisms. A potential for adverse impacts exists where contaminants, degradation by-products, and/or secondary stressors (such as low dissolved oxygen [DO]) associated with the ground-water come in contact with these biota in transition zone habitats.

The microbial community of the transition zone—via their function in carbon and nutrient cycling—has been shown to play an important, potentially beneficial role at some sites in the biodegradation and attenuation of ground-water contaminants (Lorah et al. 1997; Ford 2005). For example, at a site in Angus, Ontario, a detailed hydrogeological study indicated microbial activity in the thin transition zone of the Pine River to be responsible for significant attenuation of a chlorinated solvent plume (Conant et al. 2004). Microorganisms are often responsible for the very sharp oxidation-reduction (redox) gradients that frequently occur across the transition zone (Fenchel et al. 1988; Wetzel 2001). These biochemical changes may aid the degradation and attenuation of organic contaminants, or may release chemicals (e.g., naturally occurring iron and manganese, degradation products of the organic contaminants) from the transition zone sediments; and these in turn can affect aquatic biota. Ground-water discharge may alter microbial activity in the transition zone, reducing DO levels to the point where habitat quality and biota are adversely affected (Morse, 1995; Pardue and Patrick, 1995).

1.3 Ground-Water and Contaminant Discharges in Transition Zones

Critical to the proper evaluation of ecological risks in the transition zone is an accurate determination of the location of contaminated ground-water discharge, which is expected to occur within a broader discharge zone. Determining contaminant discharge locations may be relatively straightforward or quite complicated, depending on the location of the source(s) of ground-water contamination with respect to a surface-water body, the hydrogeologic complexity of the flow system, the temporal variability in water table and surface-water levels, and the size (both vertically and horizontally) of the plume relative to the general ground-water flow paths. Plumes of contaminants will flow from contaminant source areas to points of discharge along pathways governed by the permeability of materials, the configuration of the hydraulic gradient, and density differential with respect to the surface-water body. One should not assume that a contaminant plume will discharge at a location that represents the shortest distance from a ground-water contaminant source area to the surface-water (Woessner 2000; Conant 2004). For example, contaminants originating from a source located in an upland area adjacent to a highly permeable stream corridor may be transported by ground-water for some distance downgradient (Figure 1, location A), sometimes following ancient paleochannels in the geology, before eventually discharging to the stream.

In contrast, ground-water contamination from a site located directly upgradient and generally in direct line with the stream channel and ground-water flow may be transported to the nearest point in the stream where it may discharge completely (Figure 1, location B). In some cases, ground-water transport of some contaminants may continue on to the next meander, with additional discharge of these contaminants occurring farther downstream. A contaminated ground-water plume may also partially discharge at one location (Figure 1, location C1), with the remainder of the plume discharging at yet another downgradient location (Figure 1, location C2), or the plume may pass under the surface-water body without discharge. Similarly, at any of the discharge locations several different GW/SW exchange conditions are possible that could affect the vertical transport of contaminated ground-water into overlying waters (Figure 2).

Patterns of ground-water discharge and other ground-water/surface-water interactions vary over time. Stream reaches and lakes may change from being locations of ground-water discharge to places of surface-water recharge to the underlying deposits when water levels in the surface-water body suddenly rise or the water table in the adjacent deposits decline below the surface-water level. Daily reversals in flow direction in the transition zone can occur in tidally influenced areas. Annual erosion and deposition of sediments along a riverbed can alter patterns of discharge (such as those shown in Figure 2) by rearranging the configuration of low and high permeability deposits. Even the implementation of remedial actions can alter ground-water/surface-water interactions if they change ground-water levels. For example, pump and treat remedies could cause drawdown of the water table and change ground-water discharge zone in an adjacent surface-water body into areas of induced infiltration (recharge of surface-water into the subsurface). Ground-water/surface-water interactions are dynamic but the transition zone is defined to encompass this full range of temporal and spatial variability.

1.4 Transport and Fate of Contaminated Ground-Water in Transition Zones

Many factors influence the transport and fate of contaminated ground-water as it travels though the subsurface prior to discharging to a surface-water body. Conant (2000) summarizes some of the most important factors in the context of contaminant plumes that discharge to surface-water:

- Physical and chemical characteristics of the contaminants;
- Geometry and temporal variations in the contaminant source zone (release area);
- Transport mechanisms (advection and

dispersion); and
- Reactions (destructive and non-destructive).

The complexity and dynamic conditions of the transition zone can considerably alter the plumes passing through the zone. For example, Conant et al. (2004) found that a tetrachloroethene (PCE) ground-water plume changed its size, shape, and composition as it passed through the transition zone. Biodegradation in the top 2.5 m of the transition zone also reduced the PCE concentrations but created high concentrations of seven different transformation products thereby changing the toxicity of the plume. The biodegradation was spatially variable and concentrations in the streambed varied by a factor of 1 to 5000 over distances of less than 4 m horizontally and 2 m vertically. Widely ranging concentrations of volatile organic contaminants have also been observed in plumes discharging to lakes (Savoie et al, 2000) and wetlands (Lorah et al , 1997). These studies not only demonstrate the spatial variability of contaminant concentrations in the transition zone, but also suggest that aquatic life within the zone can be exposed to relatively high concentrations when the contamination has not yet been diluted by surface-water.

Concentrations in contaminant plume discharges can change over time. Previous discharges may have acted as sources of contamination to the transition zone thus loading the associated sediment with metals or hydrophobic organic compounds. Moreover, the pattern of ground-water flow and contaminated discharge might have been different in the past such that contaminants in those sediments may not be at the locations that current ground-water flow paths would predict. Direct sampling of the transition zone can help identify such suspected conditions. It is important to note that transport and fate factors other than ground-water flow (e.g., sorption, reaction time) need to be considered in the conceptual site model as areas of high ground-water discharge flow may not necessarily be areas where the highest concentrations will be found in the transition zone. Conant et al., (2004) observed that interstitial water having the highest concentrations of organic contaminants and degradation products occurred in low discharge areas of the streambed. This finding likely reflected sorbed, retarded, or slowly advecting plume remnants of past high-concentration discharges that had yet to get all the way through the lower permeability, organic carbon-enriched deposits (Conant et al., 2004).

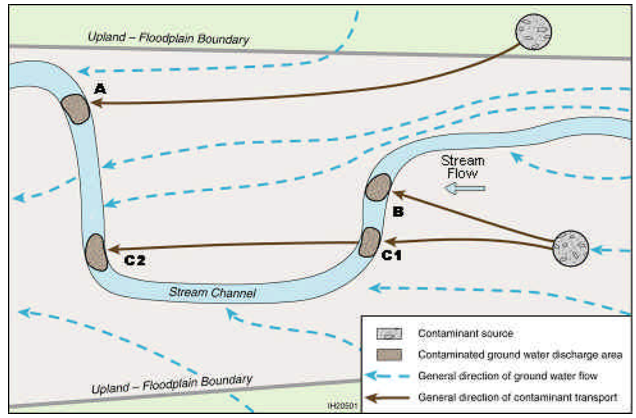


FIGURE 1 Plan View of Ground-Water Flow, Contaminant Transport, and Ground-Water Discharge Areas along a Hypothetical Stream Channel (Modified from Woessner 2000).

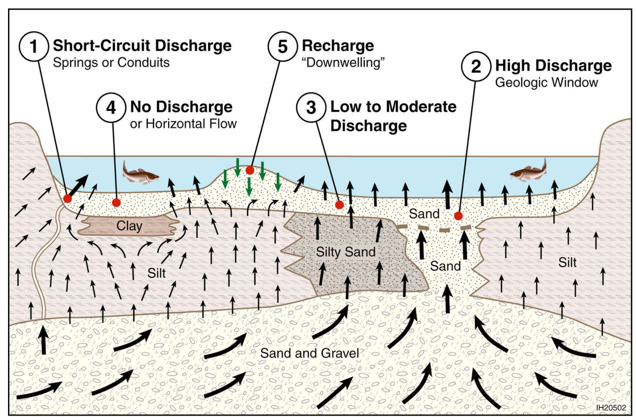


FIGURE 2 Conceptual Model of Different Types of GW/SW Exchange Conditions at the bed of a Surface-Water Body That may Affect the Transport of Contaminated Ground-Water into the Overlying Water (Modified from Conant 2004). (The arrows point in the direction of GW flow, and the arrow size depicts the relative rate of flow.).

2. Framework for Including the Transition Zone in Ecological Risk Assessments

2.1 The Ecological Risk Assessment Process and the Integrated Team

The ERA Guidance identifies an 8-step framework for designing and conducting ecological risk assessments for the Superfund Program (Text Box 1; U.S. EPA 1997). This framework describes the steps and activities needed to design and conduct scientifically defensible risk assessments that will support management decisions regarding site cleanup leading to a Record of Decision. Critical aspects of the framework are problem formulation and the associated development of a conceptual site model (CSM). Problem formulation establishes the goals and focus of the risk assessment, i.e., the ecological components and processes that are potentially harmed or at risk, as well as the assessment endpoints (specific processes, or populations/communities of organisms to be protected). The CSM characterizes the toxicological relationships between the contaminants and the assessment endpoints, as well as the exposure pathways by which the two are potentially linked (i.e., contaminant migration pathways, chemical alterations, and organism life histories; see ERA Guidance Steps 1 and 3). The CSM may also develop the risk questions to be addressed by the assessment (ERA Guidance Step 3), and identify the endpoints that will be measured (measurement endpoints) in order to provide the data necessary to address the risk questions. Because contaminants will partition among water, sediment, and organisms, a holistic CSM that includes all relevant compartments will be the most useful to guide the ERA and help determine how the partitioning has occurred or is occurring within the transition zone. This should help project managers with decisions about source control, which media to remediate, the influence of remedial work on contaminant fate and transport, and the potential for partitioning to alter the effectiveness of a proposed remedy (such as a sediment cap).

In the design and conduct of an ERA that includes transition zones and areas of ground-water discharge, it is critical that the project manager assemble a risk assessment team that is interdisciplinary and includes ecological risk assessors and hydrogeologists at a minimum. For practicality in this paper the term “hydrogeologist” is used to generically include all the team members who work mostly on the physical, hydrologic, and hydrogeologic aspects of site characterization (i.e., hydrologists, hydrogeologists,, etc.). Similarly, the term “ecologist” is used to generically include all the members who work mostly with the biological aspects (risk assessors, biologists, benthic ecologists, ichthyologists, zoologists, botanists, malacologists, limnologists, microbiologists, etc.). These disciplines should work closely together starting as early in the ERA process as possible. To adequately characterize the hydrogeological setting of a site, the hydrogeologists need to understand the local ecosystem, the habitats, the ecological endpoints to be protected from the adverse effects of ground-water-associated contaminants, and the exposure pathways that link the contamination and the endpoints. Similarly, it is critical for the ecological risk assessors to understand the spatial and temporal variability in the transition zone locations and the potential mechanisms for transport of contaminants by ground-water to surface-water. It is important to remember that the ground-water plume may not have reached the surface-water at the time of the assessment, but if it is likely to discharge to the surface-water in the future, there still is a risk of release that needs evaluation. Because, the spatial and temporal variability in ecological systems can be quite different from the hydrogeological system, the integrated team will insure data will be collected on scales useful for all disciplines. This interdisciplinary focus is most effective when initiated during problem formulation (U.S. EPA Guidance Steps 1 and 3). At this stage, the integrated assessment team will address: (1) the hydrologic regime of the site and its context in the watershed, (2) where and when ecological exposures may be occurring, (3) which organisms (and ecosystem functions) may be exposed to contaminants in the ground-water at the transition zone and associated ground-water discharge area, (4) which processes are affecting contaminants during transport (e.g., abiotic transformations, biodegradation, dispersion, diffusion, adsorption, dissolution, volatilization), (5) what additional data may be needed to support the risk assessment, and (6) the appropriate scope to fit project needs.

Text Box 1: The 8-Step Ecological Risk Assessment Process for Superfund (U.S. EPA 1997)

Step 1: Screening-Level Problem Formulation and Ecological Effects Evaluation
Step 2: Screening-Level Exposure Estimate and Risk Calculation
Step 3: Baseline Risk Assessment Problem Formulation
Step 4: Study Design and Data Quality Objectives Process
Step 5: Field Verification of Sampling Design
Step 6: Site Investigation and Analysis Phase
Step 7: Risk Characterization
Step 8: Risk Management

2.2 Including the Transition Zone in Designing and Conducting Ecological Risk Assessments

It is often difficult to describe complete exposure pathways when contaminants move among multiple environmental media and habitats. In aquatic systems, it is critical to recognize the static, dynamic, and interactive aspects of different media and their associated habitats. Currently, with ERAs that have ground-water and surface-water interactions, problem formulation and the CSM typically identify the contaminant source area, the ground-water flow paths from the contaminant source area, the surface-waters that receive discharge of contaminated ground-water, the media that may be contaminated (e.g., ground-water, surface-water, and sediment), and the habitats and ecological receptors that occur in those surface-waters. While these ERAs often include some aspects of the transition zone in the CSM, they more often do not specifically consider the ecological importance of the transition zone nor the relationships and interactions among ground-water flow, surface-water hydrology, sediment dynamics, and the transition zone biota. Rather, these ERAs typically evaluate only the biota associated directly with the sediment/water interface and/or with the overlying water column for adverse ecological impacts**.** In such ERAs, there is no explicit consideration of a transition zone, only a boundary line that separates ground-water and surface-water that is assumed to be the sediment/surface-water interface. Hence, the biota and ecological processes associated with this zone may not be appropriately considered during problem formulation. Appropriate consideration of the transition zone means that exposure, pathways, and potential effects are evaluated in a manner sufficient to meet the purpose of the ERA set forth in EPA guidance as indicated in Section 1.1 above. An effective approach to developing a CSM is illustrated in Figure 3. This can be adapted to accommodate a variety of different ground-water/surface-water settings such as wetlands (Lorah et al. 1997) and estuaries (Fetter 2000).

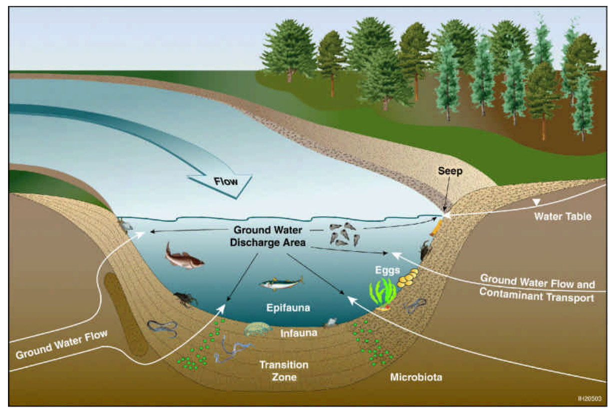


FIGURE 3 Conceptual Site Model Depicting Contaminant Transport via Ground-Water Flow, Followed by Discharge Through the Bedded Sediments in the Transition Zone into Overlying Surface-Water

2.2.1 Framework for Incorporating the Transition Zone into Problem Formulation

Consideration of the transition zone should begin as early as possible in the 8-step ERA process, preferably during problem formulation and CSM development. It cannot be overemphasized that problem formulation and the CSM should be based on the combined knowledge of the interdisciplinary team approach which includes hydrogeologists and ecologists on the team, at a minimum, and preferably should include the critical review of other team members, such as the project manager and a toxicologist. The following 5-step framework has been designed to incorporate the transition zone into problem formulation of the ERA process and to help develop a comprehensive ground-water/transition zone/surface-water CSM for any aquatic ecosystem.

Step 1 Review available site-related chemistry data to identify known or potential contamination

Step 2 Identify the hydrogeological regime and potential fate and transport mechanisms for ground-water contaminants, including (a) identification of areas of contaminated ground-water discharge and (b) the spatial and temporal variability in the magnitude and location of the discharges.

Step 3 Identify ecological resources at areas of ground-water discharge, including associated transition zones.

Step 4 Identify ecological endpoints and surrogate receptors.

Step 5 Develop a dynamic CSM and associated risk hypotheses and questions.

The activities in these steps usually take place during the design and conduct of an ERA, and thus do not necessarily identify activities that would be in addition to those normally developed when following the U.S. EPA 8-step process for an ERA (Text Box 1). In addition, due to the relationship between the CSM and ecological endpoints, the risk assessment team may find it useful to revisit these steps as they refine both the CSM and selection of endpoints.

Step 1 ***Review available site-related chemistry data to identify known or potential contamination***. In this step, the team determines if there is a potential for the ground-water to be contaminated, and, if so, whether the contaminants could be transported through the transition zone into overlying surface-water. Specifically, the team will focus on the question: *Is there known or potential (1) ground-water contamination and/or (2) sediment or surface-water contamination related to ground-water, and, (3) if so, by what contaminants?* The answer to this question will be based on a review of the historical site-related chemistry data regarding the source (i.e., the nature of the release and the known or suspected contaminants), potential contaminant migration pathways, and the affected environmental media (i.e., evidence of contamination in soil, ground-water, sediment, biota, and/or surface-water, including transformation products). This information will also be used to determine which contaminants may be encountered by ecological resources associated with the site. If it is determined that contamination is present or likely, the extent of contamination in discharging ground-water will need to be characterized.

Step 2 ***Identify the hydrogeological regime and potential fate and transport mechanisms for ground-water contaminants, including (a) identification of areas of contaminated ground-water discharge and (b) spatial and temporal variability in the magnitude and location of ground-water discharge.*** The nature and extent of GW/SW interactions at a site and the specific locations of ground-water discharge areas are important in the determination of potential exposure points for ecological receptors. In this step, the hydrogeologist and ecological risk assessor delineate contaminated areas and identify areas of contaminated ground-water discharge (and associated transition zones). The focus of this step is to address the question: *Where is the contamination and where is contaminated ground-water reaching the transition zone and then discharging to the surface?* Potentially contaminated ground-water discharge areas can be identified on the basis of:

- Available chemical and hydrologic data from site wells and shoreline work in the area (e.g., ground-water chemistry, NAPL presence, aquifer extent, preferential pathways, hydraulic conductivity, hydraulic gradients and flow directions [vertical and horizontal], water table elevation, and seasonal precipitation patterns);
- Physical features indicative of a ground-water discharge area may be identified during a site visit including seeps, pools in streams, and plant species that prefer ground-water discharge;
- Direct investigations during the site visit to locate and delineate ground-water discharges (e.g., using simple measurement techniques such as temperature or conductivity probes, minipiezometers with manometers or differential pressure gauges, or seepage meters; observations of certain plant species, areas of mineral precipitation, or areas with sheens; geophysics to map and track plumes);
- Direct investigations of contamination in the transition zone (e.g., sampling interstitial water using minipiezometers, miniprofilers, passive diffusion samplers), including temporal variability.

Step 3 ***Identify ecological resources in areas of ground-water discharge, including associated transition zones.*** As areas of ground-water discharge are identified, the ecological risk assessors will evaluate the conditions at these locations and in the overlying surface-water to identify the types of ecological resources that occur (or could occur) and be exposed to the ground-water-associated contaminants. The focus of this step is to address the question: *What are the ecological resources at risk from exposure to ground-water contamination at this location?* The risk assessors will make this determination on the basis of observations made during a site visit and through a review of available ecological data for the site. Ecological resources may include habitats, species, populations, and communities that occur at or utilize the ground-water discharge areas, the associated transition zones and sediments, and the surrounding surface-waters. These resources may be exposed directly or indirectly through the food web.

Step 4 ***Identify ecological endpoints and surrogate receptors***. The habitats that will be associated with areas of ground-water discharge may support a wide variety and diversity of biota that could be exposed to contaminants in the ground-water. However, it is not feasible or practicable to directly evaluate all of these biota. Instead, a few assessment endpoints (Text Box 2) are selected to represent risks to all of the individual components of the ecosystem (U.S. EPA 1992; 1997). In this step, the ecological risk assessors will identify appropriate assessment endpoints on the basis of:

- Contaminants and their concentrations,
- Potentially complete exposure pathways linking the contaminants with the endpoints,
- Mechanisms of toxicity of the contaminants and knowledge of the potential susceptibility of the endpoints to the contaminants, and
- Ecological relevance of the endpoint.

Detailed guidance on selecting assessment endpoints and linking them to risk determinations may be found in U.S. EPA (1997).

Text Box 2: Endpoints and Surrogate Receptors

Assessment Endpoint: an explicit expression of the environmental value(s) to be protected. Individual assessment endpoints typically encompass a group of species or populations with some common characteristic, such as a specific exposure route or contaminant sensitivity, or the typical structure and function of biological communities or ecosystems associated with the site (U.S. EPA 1992, 1997).

Measurement Endpoint: a measurable ecological characteristic that is related to the valued characteristic chosen as the assessment endpoint. The measurement endpoint provides measures of exposure and/or effects (U.S. EPA 1992, 1997).

Surrogate Species: a species that is considered to be representative of the assessment endpoint and for which measurement endpoints may be selected and on which the risk characterization will focus.

Assessment endpoints for the transition zone will focus on the protection of (1) the biota that live within or utilize the transition zone or the ground-water discharge area (including interstitial water, sediment, and surface-water), (2) other biota that may be exposed to the ground-water contaminants either through direct contact or indirectly through ingestion of food or sediment contaminated by the ground-water, and (3) the ecological functions of these biota (e.g., productivity, benthic respiration, biodegradation). For example, transition zone assessment endpoints may include the maintenance and sustainability of the infaunal community of the transition zone, maintenance and sustainability of conditions that support fish and other surface-water species that seek out ground-water discharge zones as habitat or refugia, or maintenance of the epifaunal community inhabiting the ground-water discharge areas. For such assessment endpoints, surrogate receptors (Text Box 2) for the transition zone may include microbial functions; infaunal organisms or communities (e.g., meiofauna, or macrobenthic invertebrates). Other surrogates may include epifaunal organisms such as plants and bottom fish, as well as life stages of various organisms such as incubating fish eggs.

In the case of a baseline ERA, one or more measurement endpoints (Text Box 2) will be selected to evaluate each assessment endpoint. These measurement endpoints could include benthic macroinvertebrate abundance and diversity; the survival, growth, or reproduction of the surrogate receptors as measured by laboratory and *in situ* toxicity tests or microcosms; the concentration of contaminants in the tissues of surrogate species (as a result of bioaccumulation or bioconcentration); sediment or ground-water concentrations; or concentrations in diffusion samplers. Because there are currently no methods available to risk assessors that allow for decision-based interpretations of changes in transition zone-associated organisms (especially with regard to the microbial community), the choice of surrogate receptors and associated measurement endpoints used to address the assessment endpoints for the transition zone may be limited to species and measurement endpoints for which methods are available.

Step 5 ***Develop a CSM and associated risk hypotheses and questions***. In this step, the information and results of the preceding steps will be used to develop a CSM that identifies the known or assumed relationships among the contaminant source, the environmental fate and transport of the contaminants in the ground-water, and the assessment endpoints that may be exposed to the contaminants (Figure 3). The CSM should also identify the potential effects that the assessment endpoints may incur from the exposure. These relationships represent working hypotheses of how the ground-water contaminants are moving or will move through the environment (i.e., moving through the transition zone discharging to overlying surface-waters) and affecting the assessment endpoints (associated with the transition zone and overlying sediments and surface-waters). The CSM thus helps to conceptualize the relationships between contaminants and assessment endpoints, frames the questions that need to be addressed by the risk assessment, and aids in identifying data gaps for which the collection of environmental data may be necessary.

Risk questions about the relationships between the assessment endpoints and their predicted responses when exposed to contaminated ground-water discharges can be developed along with the CSM. These risk questions provide additional bases for the selection of appropriate measurement endpoints and study designs. Some examples of risk questions for the transition zone include (1) Does contaminant exposure exist at ground-water discharge points, and, if so, do the exposure concentrations exceed levels considered “safe” for the assessment endpoints? (2) Are exposures to contaminants at ground-water discharge points associated with deleterious effects to the assessment endpoints? (3) Does the exposure to contaminated ground-water pose unacceptable risks to transition zone, benthic, and/or surface-water assessment endpoints?

2.2.2 Hydrologic Regime and Contaminant Fate and Transport Considerations during Problem Formulation

As in any ground-water setting, the transport and fate of contaminants will be a function of the characteristics of the geologic materials through which ground-water is passing, the chemical and physical characteristics of the native ground-water, and the physical and chemical characteristics of the contaminants. In the transition zone, the mixing of surface- and ground-waters can create steep gradients (large changes over relatively short distances) in water quality parameters such as DO concentration, salinity/conductivity, oxidation-reduction potential (ORP), pH or temperature which can be measured in the field, and hardness, solids, and Acid Volatile Sulfides which can be measured in the lab. The characteristics of the substrate (especially sediments) such as mineral content, grain size, porosity, and TOC in the transition zone may also change abruptly over relatively short distances. Each of these characteristics can strongly influence contaminant mobility. Contaminants that have traveled considerable distances in ground-water with little alteration may, upon entering and passing through a transition zone, show rapid attenuation in this zone due to the dynamic physical and chemical characteristics of the zone. These changing conditions, as contaminants move from the ground-water environment to the transition zone, can facilitate attenuation processes such as adsorption, microbial degradation of chlorinated solvents, and precipitation of some dissolved metals.

On the basis of these characteristics of the transition zone, two key hydrogeologic questions to consider in problem formulation are (1) How close to the ecological resources are the contaminants or their degradation or oxidation/reduction products? and (2) What are the transport and attenuation processes controlling the mobilization, movement, flux, mass loading, and observed distribution of contaminants? In considering these questions in problem formulation it may be beneficial to understand the role of smaller scale changes in permeability, mobilization (such as ground-water moving through contaminated sediment, etc.), movement of contaminants in whatever form they are found (such as dissolved, NAPL, colloid-bound, etc.), and where the contaminants ultimately come to reside.

Various GW/SW exchange conditions are possible at the bed of any surface-water body (Figure 2) (Conant 2001, 2004). There may be situations where no ground-water discharges into surface-water because the hydraulic gradient is horizontal (Figure 2, No. 4), the hydraulic gradient is away from the surface-water body (e.g., downward vertical gradient; Figure 2, No. 5), or a geologic barrier is present that prevents discharge (Figure 2, No. 4). Alternatively, ground-water discharge may occur at a low rate due to a low hydraulic gradient and/or the presence of low to moderate permeability materials that act to slow the ground-water flow (Figure 2, No. 3).

In contrast to the above exchange conditions, the presence of a strong hydraulic gradient and/or highly permeable substrate may result in a condition where the ground-water is able to rapidly discharge with little opportunity for attenuation. In this instance, contaminants come in contact with organisms that not only live within the sediment but also live on or use the sediment surface or overlying surface-water or even preferentially seek out these areas for spawning or as thermal refugia (Figure 2, No. 2). Ground-water discharge areas exhibiting this last exchange condition may be viewed either as geologic windows that are easily detected (Figure 2, No. 2) or as small "short circuits" in otherwise no- or low-inflow zones (Figure 2, No. 1) (Conant 2004). The overall density and distribution of such short circuits may be key factors in determining whether or not they drive a significant ecological risk. It is important to remember that in any setting, ground-water flow rate and direction are controlled by hydrologic conditions. These conditions can be highly variable, and multiple sampling events conducted over time, or other tools that integrate exposure or effects over time, may be needed to characterize the transition zone.

3. Tools for Characterizing the Hydrogeology and Ecology of the Transition Zone

A variety of tools are available that can be used to help locate and characterize areas of contaminated ground-water discharge and associated transition zones (EPA 2000; see Table 1 for some site-specific examples). Similarly, there are a number of tools and approaches available for characterizing the ecological resources of the transition zone and for evaluating the exposure of, and effects on, those resources exposed to contaminated ground-water. The choice of tools will depend on the environment, the selected assessment and measurement endpoints, and use of the Data Quality Objectives Process will help the site team avoid sampling method bias. While Tables 2 and 3 highlight commonly used tools for characterizing the hydrogeology and ecology of the transition zone, additional tools are identified in *A Compendium of Chemical, Physical and Biological Methods for Assessing and Monitoring the Remediation of Contaminated Sediment Sites* (U.S. EPA, 2003).

3.1 Hydrogeological Characterization

The identification and characterization of contaminated ground-water may occur during the screening ERA (Steps 1 and 2 of the 5-step transition zone framework) and continue during the baseline ERA. During the screening ERA, this hydrological characterization may be based, in part, on

- Examination of existing maps of surficial and bedrock geology and the local hydrology;
- Examination of water chemistry data from existing wells, piezometers, and surface-water;
- Examination of boring logs and other geologic data;
- Evaluation of ground-water migration and preferential pathways;
- Collection and examination of remotely sensed thermal data;

TABLE 1 Examples of Case Studies Where Ground-Water and Surface-Water Investigations Were Employed to Answer Site-Specific Questions Regarding Ground-Water Contaminant Exposure, Risks, and Management			
Site	Environmental Setting/Issue	Ground-Water Contaminant Concern/Question	Nature of Ground-Water/Surface-Water Investigation
ASARCO Tacoma Smelter, Tacoma, WA	Metal smelting with arsenic in ground-water adjacent to Puget Sound.	Is the arsenic, in parts per thousand, in ground-water discharges to the shoreline and subtidal zones likely to cause an adverse impact.	Arsenic speciation and electron probe analysis show pH and redox increase when ground-water goes through the transition zone results in precipitation and the arsenic does not enter the marine environment
Eagle Harbor, WA	Marine habitat, Puget Sound.	Identify zones of discharge to harbor floor.	Towed temperature and conductivity probe linked ground-water in the uplands with discharges to harbor sediment.
Eastland Woolen Mill, East Sebasticook River, ME	River system impacted by chlorinated solvents from former woolen mill.	Is contaminated ground-water contributing to sediment toxicity?	*In situ* and laboratory toxicity tests, nested multilevel minipiezometers demonstrated spatial pattern of chlorobenzene transport and toxicity (Greenberg et al.,2002). Microbial and meiofaunal analyses documented changes in those communities.
Leviathan Mine, CA	Open-pit sulfur mine at 7,000 ft in Sierra Nevada Mountains, with acidic discharge into Leviathan Creek.	In highly mineralized geologic setting, what is relative contribution of acid mine drainage and natural acidic discharge to water quality of the watershed?	Investigation of Leviathan Creek using a hand-held combined conductivity, pH, and temperature meter revealed a single small natural seep, compared to large inputs from the mine.
McCormick & Baxter Creosoting Co., Portland, OR http://www.deq.state.or.us/nwr/mccormick.htm	Site adjacent to Willamette River. Site used creosote, pentachlorophenol, and metals for wood treatment.	Is there seepage of creosote or other contaminants to the river via ground-water?	Working with divers collecting sediment samples and installing minipiezometers and seepage meters within river, documented non-aqueous phase liquid (NAPL) discharges from just below sediment surface and ground-water discharge at the shoreline and deeper in the river.
St. Joseph, MI	Chlorinated solvent ground-water plume migrating toward Lake Michigan.	Is natural attenuation sufficient to keep contaminants from reaching the lake?	Geoprobes with slotted screens were used to identify an offshore solvent plume discharge zone, demonstrating that natural attenuation was not completely effective at this site (Lendvay et al. 1998). In 1999, pore water sampling of the near shore sediments identified the main plume discharge (MDEQ 2005).
Treasure Island Naval Station, San Francisco, CA	Chlorinated solvent plume migrating toward/into San Francisco Bay.	Location of ground-water control monitoring points(water column measurements or wells and location of wells, if chosen).	The Navy agreed to place monitoring wells at locations where a study of tidal mixing in the ground-water revealed a 20% influence of seawater; this made the GW/SW transition zone the remedial compliance point.
Western Processing, Kent, WA	Small stream (Mill Creek) along site boundary. Contaminated ground-water discharging to stream.	Are stream sediments contaminated with solvents and metals, and, if so, what is the source of the contamination? Could a simple removal of the contaminated sediments address the ecological risks?	Standpipes in the creek indicated artesian flow. Solvent contamination was found to originate from surface input, while the metals contamination was due to the discharge of contaminated ground-water.
Chevron Mining Inc. (CMI) (formerly Molycorp, Inc.), Questa, NM	Molybdenum mine near the Red River which is a tributary to the Rio Grande. Metal and low pH loads to the river system from ground-water upwelling.	Do the concentrations of COPCs in discharging ground-water, surface water, and/or sediments in upwelling exposure areas pose unacceptable risks to aquatic life?	Laboratory and *in situ* toxicity tests, multilevel minipiezometers, exposure chemistry, benthic and fish community analyses were used to identify two specific discharge points along the study area as requiring evaluation during the Feasibility Study.

- Site walkovers for visible signs of discharge (such as areas of differing sediment grain size and structure or obvious seeps observable under the low-river stage or tide conditions); and
- Site walkovers using portable (hand-held) monitoring instruments such as salinity/conductivity, pH, DO meters, and/or temperature probes;
- Geophysical survey to characterize the underlying geology and directly or indirectly detect contaminated ground-water.

The use of “standard” monitoring wells and piezometers to characterize conditions within the transition zone may not be feasible, as these tools will typically be too large to use in a transition zone environment. A number of relatively inexpensive and simple portable instruments are available that may be used to locate areas of contaminated ground-water discharge. These instruments include:

- Passive Diffusion Samplers
- Peepers,
- Miniprofilers,
- Pushpoint pore-water samplers,
- Minipoint samplers,
- Sippers,
- Hydraulic potentiomanometers
- Seepage meters.

For the baseline ERA, additional hydrogeological characterization data may be needed to evaluate the assessment and measurement endpoints and address the risk hypotheses and questions (see Step 4 of the transition zone CSM framework). Portable instruments can be used to (1) rapidly and inexpensively identify and characterize ground-water discharge areas, (2) support a screening-level risk assessment, and (3) yield quantitative contaminant data of sufficient quality to support the needs of a baseline ERA. The instruments that could be implemented at a specific site will be based on the CSM and the capabilities and metrics of the individual tools. Because different tools may have quite different metrics, site characterization will benefit greatly from early consideration of how the data will be evaluated, interpreted, and integrated. When tools cannot effectively sample the zone of primary interest, consideration can be given to sampling in adjacent zones, provided agreements are reached how the data will be interpreted in the ERA. Brief descriptions of tools for hydrological characterization are presented in Table 2. Additional information regarding the sampling of ground-water and interstitial water can be found at:

- http://clu-in.org/techdrct/,
- http://www.epa.gov/tio/tsp/issue.htm
- http://www.ert.org/.

3.2 Characterization of Ecological Resources, Their Exposures, and Resulting Effects

Numerous tools and approaches are available for characterizing the ecological resources of a transition zone and for evaluating the effects of exposure to ground-water contamination (Williams 1999). These include survey protocols using a variety of devices to sample and/or analyze periphyton, benthic invertebrates, and fish (e.g., Barbour et al. 1999) and the microbial community (e.g., Adamus 1995; Hendricks et al. 1996; Williams 1999) (Table 3). These tools may be used to identify the types and abundances of species, characterize the structure of the ecological communities, and evaluate microbial processes of the transition zone and associated ground-water discharge areas.

Exposure of transition zone biota may be inferred from survey data by spatially linking survey habitats with the presence of contaminated ground-water (as determined using the previously described hydrogeological characterization tools). Uptake of ground-water contamination by biota may be estimated, and exposures characterized, using *in situ* approaches such as the direct analysis of ground-water-associated contaminants in biota that inhabit the transition zone and associated areas, or through the chemical analysis of test organisms following controlled exposure in areas of contaminated ground-water. Exposure of transition zone biota may be estimated using semipermeable membrane devices (SPMDs) to estimate potential uptake of ground-water contamination by exposed biota (limitations can be minimized by field calibration at the site of interest—see Section 4.2). Exposure levels may also be inferred through the use of contaminant uptake factors (such as bioconcentration factors [BCFs]) that are available in the scientific literature for many chemicals. Effects can be inferred from traditional tools applied to the transition zone (e.g., in-situ toxicity tests, comparison with criteria or risk-based concentrations for various media).

4. Evaluating Ecological Risks in the Transition Zone and Associated Ground-water Discharge Areas

Ecological risks to most biota in the transition zone and discharge area from exposure to contaminated ground-water can be effectively predicted by (1) evaluating ground-water chemistry at the transition zone and (2) estimating the resulting direct and indirect ecological effects from that exposure. Other approaches can be very useful when needed to reduce uncertainty regarding effects on the selected assessment endpoints. These evaluations may be directly incorporated into the 8-step process for designing and conducting ERAs (U.S. EPA 1997; see Section 2.1). Decisions regarding risk acceptability and subsequent risk-management decisions can be made based on the outcomes of these evaluations. Figure 4 presents an example of a decision tree for assessing ecological risks associated with the discharge of contaminated ground-water through the transition zone. If unacceptable risks are identified and remediation is appropriate, the ERA should ultimately provide risk-based preliminary remediation goals (PRGs) and will assist in the identification and evaluation of remedial alternatives and in the evaluation of remedial success (U.S. EPA 1994a, 1997).

4.1 Evaluation of Ground-water and Transition Zone Water Chemistry

The concentrations of chemicals in the ground-water and transition zone waters can be evaluated in the screening and baseline ERAs (Figure 4). These evaluations compare measured chemical concentrations to benchmark values that represent water concentrations considered protective of exposed aquatic biota. Chemicals present at concentrations below the benchmark values are assumed to pose acceptable risks to the transition zone biota. The baseline ERA may also employ evaluations of exposure and effects to support a risk characterization.

4.1.1 Evaluating Ground-Water Chemistry in the Screening-Level Risk Assessment

In the screening-level ERA, the maximum chemical concentration detected in ground-water is compared to applicable benchmark values (Step 2 of the Superfund ERA process [U.S. EPA 1997]). Use of maximum detected concentrations of the contaminants is consistent with the use of conservative assumptions in the screening-level ERA. The benchmark values used in the screening ERA are the Ambient Water Quality Criteria (AWQC) (U.S. EPA 2002a), which identify concentrations of selected chemicals that are considered protective of aquatic biota under chronic exposures in fresh and marine waters (see Text Box 3). Because the AWQC are considered protective of benthic organisms, they are suitable for evaluating transition zone organisms. When an AWQC is not available for a specific chemical (e.g., many volatile organic compounds), an alternative screening value may be selected (U.S. EPA 1997), or the chemical is carried forward into the baseline ERA for further analysis by another approach. The ground-water concentrations should be compared with the lowest appropriate chronic criteria. In brackish systems, both freshwater and marine chronic criteria should be considered. The assumptions regarding the applicability of AWQC or other benchmarks for evaluating potential ecological risks to transition zone biota should be discussed in the uncertainty analysis that is part of the risk assessment (U.S. EPA 1997).

Chemicals with maximum ground-water concentrations below the AWQC are assumed to pose negligible ecological risk and that chemical-specific ground-water pathway can be removed from further consideration in the ERA (Figure 4), while those with concentrations exceeding benchmark levels are further evaluated in the baseline ERA. Depending on the potentially complete exposure pathways identified in the CSM, chemicals may need to be evaluated in other media such as sediment or tissue.

TABLE 2 Tools That May Aid in the Identification and Characterization of Areas of Contaminated Ground-Water Discharge	
Tool	Description
Direct Push Technology	Vibracores and Geoprobes are examples of direct push sampling tools that can be used in the sediments to obtain sediment cores and samples, and, with adaptations, to obtain water samples at depth below the sediment surface.
Geologic and topographic maps	Surficial and, in some settings, bedrock geologic maps of the stream and near-stream environment may indicate which zones are most likely to have significant interchange between ground-water and surface-water.
Hydraulic potentiomanometer	Winter et al. (1988) present a device that consists of a stainless steel probe with a screened section near the tip that is connected by a tube to a manometer whose other tube can be placed within a surface-water to measure the head difference between ground and surface-water at a sampling station. The device can also be used to obtain ground-water samples by detaching the probe from the manometer and withdrawing a sample with a hand pump.
Minipoint sampler	Duff et al. (1998) present a sampler that has six small-diameter stainless steel tubes set in a 10-cm-diameter array preset to drive depths of 2.5, 5.0. 7.5, 10.0, 12.5, and 15.0 cm. Ground-water samples from all depths are withdrawn simultaneously by a peristaltic pump.
"Mini" Profiler	Conanat et al. (2004) modified a soil vapor probe by Hughes et al. (1992), creating a miniature hand-driven version of a profiler that can be used to recover interstitial water samples from multiple depths in the same hole to a depth of 1.5m. The mini Profiler is a thin-walled tube (0.64 mm OD) with a drive point that contains small-screened ports. Pumping distilled water down the device and through the ports during driving keeps the ports free of material. In sampling mode, a pump purges the device of distilled water and draws a formation water sample up to the surface. The full-size Waterloo Profiler can be used to depths of 10s of meters (Pitkin et al., 1999).
Passive diffusion sampler (PDS)	Vroblesky and Hyde (1997) and Vroblesky et al. (1996, 1999) present development of an inexpensive sampler that collects volatile organic compounds (VOCs) by diffusion and has been successfully used at a number of sites to detect where VOC plumes are discharging to surface-water. Results provide an estimate of average concentration in the sampled water. Independent data are needed to determine flow direction past the sampler (i.e., if the sampler is collecting ground-water or surface-water). For additional information, see: http://ma.water.usgs.gov/publications/wrir/ wri024186/report.htm. PDSs have been developed for other contaminants (e.g. metals).
Peepers	Hesslein (1976) and Mayer (1976) first developed diffusive equilibration samplers in which the sampler consists of a vertical array of deionized water-filled chambers separated from interstitial water by a dialysis membrane. A number of modifications to this basic sampler now exist (USEPA 2001b; Burton et al. 2005). Results and limitations are similar to those encountered with PDSs above.
PushPoint interstitial water sampler	MDEQ (2006, in review) presents a sampler that consists of a thin-walled metal tube with a chisel-pointed tip and a 4-cm screened interval above this tip. A retractable stainless-steel plug prevents clogging of the screen during driving into the sediment. At the desired depth, an interstitial water sample can be removed by a syringe or peristaltic pump attached to the top of the device. For additional information on push-point sampling, see Zimmerman et al. (2005).
Radiologic analyses	Krest and Harvey (2003) describe a method using radioactive tracers (which can be quantified much more precisely than most organic chemicals), best used in areas with very low hydraulic gradient without the potential confounding factors such as salinity change.
Remotely sensed thermal data	Airborne forward-looking infrared radiometry (FLIR) thermal-imagery equipment. Helicopter-mounted FLIR equipment takes infrared photographs of the rivers to provide visual images of surface-water temperatures. Areas of ground-water discharge may be indicated if there is sufficient temperature contrast between the discharging ground-water and surrounding surface-water temperatures. For additional information, go to: http://geopubs.wr.usgs.gov/open-file/ of02-367/of02-367.pdf and http://www.ecy.wa.gov/pubs/0110041.pdf.
Sediment probe	Lee (1985) developed a sediment probe that is towed in contact with bottom sediments and detects zones of plume discharge by detection of conductivity anomalies. Other researchers have also used conductivity or resistivity measurements successfully but with more traditional, labor-intensive devices
Seepage meter	Unlike the devices discussed above, the seepage meter can give a discharge rate and flow direction through a stream bed. The basic seepage meter design originally presented by Lee (1977) and Lee and Cherry (1978), consists of the top section of a steel drum with a plastic bag attached as a sample collector. A variation on this design is the UltraSeep, system which is instrumented to monitor conductivity, temperature and fluid seepage rate (http://clu-in.org/programs/21m2/navytools/gsw/). A basic seepage device is driven into the sediment, and natural seepage is allowed to fill the sample bag. The volume obtained during deployment can be sampled for analysis as well as used to calculate a seepage rate. If it is known that seepage is into the streambed, the bag can be pre-filled with a known volume of water to allow seepage into the sediment and calculation of the seepage rate. While there are a number of uncertainties associated with the use of seepage meters, these meters can provide a measure of what is coming through the sediment and into surface-water that no other device can provide.
Sippers	Zimmerman et al. (1978) and Montgomery et al. (1979) present a sampler that consists of a hollow PVC stake with a porous Teflon® collar. The device has a sampling tube that runs its full length and a gas port at the top. The device is driven into the sediment and evacuated with a hand pump. Interstitial water then seeps into the device. The sample is removed by displacement with argon gas pumped in through the gas port. The initial filling of the device through application of a vacuum may limit its utility in sampling VOCs.
Site walkovers with handheld meters	Wading a shallow site with appropriate field sampling devices (e.g., temperature, pH, or conductivity meters) may be useful to preliminarily delineate some contaminant plumes. This may be especially useful in settings with ground-water discharge through discrete seeps where the measured parameters have steep gradients.

TABLE 3 Tools That May Aid in the Characterization of Ecological Resources of the Transition Zone and in the Evaluation of the Effects of Exposure of Those Resources to Contaminated Ground-Water

Tool	Description
Invertebrate community survey protocols	These protocols may include sampling devices such as sediment cores and colonization samplers (e.g., rock baskets, trays of sediment) to collect invertebrates of the infaunal communities at the ground-water discharge area. The transition zone community can be considered a simple extension of the infaunal communities. Sediment core samples are taken from the biologically active zone, which may be fairly deep (ca. 1 m) or fairly shallow (a few cm), or targeted to reach specific macroinvertebrates such as burrowing shrimp or bivalves (perhaps >1 m). Colonization samplers can be placed on the bottom of a water body as a means of collecting macroinvertebrate fauna. Following sampling, the collected biota can be analyzed using well-established bioassessment methods (e.g., as described in Barbour et al. 1999). The use of invertebrate surveys has proven effective in evaluating contaminated ground-water (Malard et al. 1996). When compared to uncontaminated sites, the results can reveal whether the invertebrate community has been affected by the exposure.
Laboratory interstitial water and sediment toxicity tests	These are traditional toxicity tests (U.S. EPA 1994b,e) that can be conducted on samples obtained from various locations in the transition zone. However, care must be taken to maintain the chemistry (redox, pH) and physical structure of the sample, and to prevent volatilization of contaminants.
Microbial community survey protocols	There are well-established methods for investigating microbial communities at the GW/SW transition zone (e.g., Hendricks 1996). The results of the survey may be useful to show whether there are differences between the microbial communities in contaminated and uncontaminated ground-water discharge zones.
Tissue analysis of resident biota (bioaccumulation measures)	Biota are collected from the transition zone and/or areas of ground-water discharge and associated surface-waters and analyzed for the ground-water contaminants.

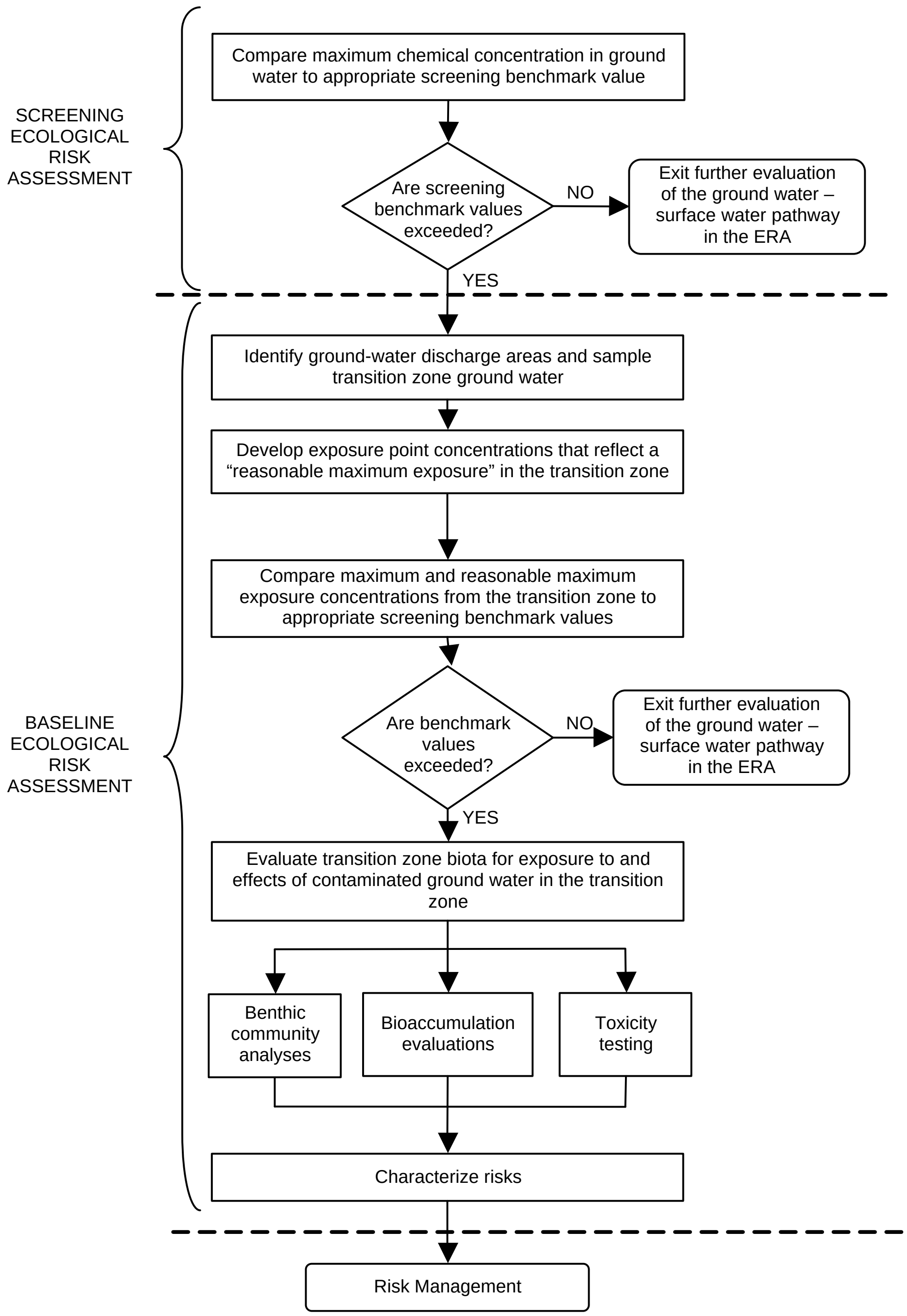


FIGURE 4 An Example Decision Tree for Evaluating Ecological Risks Associated with the Discharge of Contaminated Ground-Water through the Transition Zone.

Text Box 3: Using AWQC in GW/SW ERAs

As done for any ecological risk assessment, the assessor should determine whether the specific AWQC are appropriately protective of benthic infaunal and epifaunal organisms exposed to discharging contaminants. This determination, although difficult if AWQC are not available for certain contaminants, may be important where volatile contaminants are discharged. In these cases, reviewing the derivation of the AWQC may help determine an appropriate site-specific screening level, help select investigatory tools in the baseline ERA, or help with the uncertainty analysis.

Typically, screening-level ERAs rely on previously available data. Thus, the equipment and methods used to provide the ground-water data (see Table 2) may have been selected and implemented prior to the involvement of the ecological risk assessor. In some cases, the available ground-water data may be from wells screened below the aquifer that is discharging to surface-water. Therefore, the risk assessor should confirm that the ground-water data are acceptable and that the samples are appropriately representative for their intended use in the screening-level risk assessment. Additional information on ground-water sampling is presented in a Ground Water Forum Issue Paper (U.S. EPA 2002b). The ecological risk assessor should also determine whether the detection limits for the ground-water data will support a meaningful comparison to the benchmark values (e.g., whether the detection limits are at or below the screening values). If the ground-water data are not appropriate with regard to sampling issues and detection limits, they may have reduced value for the screening ERA.

4.1.2 Evaluating Transition Zone Water Chemistry in the Baseline Risk Assessment

In the baseline ERA (U.S. EPA 1997), chemical concentrations in ground-water at the transition zone are compared to AWQC (U.S. EPA 2002a) or other benchmark values for protection of aquatic life, but using more realistic exposure-point concentrations than those evaluated in the screening ERA. These new comparisons will not use maximum detected ground-water concentrations as in the screening ERA, but rather use exposure-point concentrations that are reasonably anticipated or expected to exist or occur at a site (the reasonable maximum exposure). Reasonable exposure point concentrations can be determined, in consultation with the site hydrogeologist, from a particular well or set of wells along the flow path(s) from the source to the discharge zone in the surface-water. However, it may be preferable to determine this more realistic exposure-point concentration from available or new data from transition zone samples. When new data are to be collected, the risk assessment team should jointly develop the sampling design. Similarly, if there are concerns for human health impacts, usually from foodweb magnification, then the sampling design should also be coordinated with the appropriate human health risk assessors.

Sampling-design considerations for the baseline ERA should include both hydrogeologic and ecological factors. Hydrogeologic factors may include ground-water and surface-water dynamics and seasonal variability, water table elevation, surface-water level and flow rates, bed material, locations of paleochannels, preferential ground-water flow paths, and contaminant concentrations in interstitial water from the transition zone. Ecological factors may include the types and distributions of biota associated with the transition zone and ground-water discharge areas, their contribution to the food web, and life history aspects of the biota such as seasonal occurrence and the vertical distribution and movement of the biota within the sediment. The collection of new ground-water data for use in the ERA may utilize one or more of the sampling tools identified in Table 2 for characterizing hydrologic conditions. Generally, these sampling tools fall into two broad categories: (1) tools that actively collect a sample at a specific time period (e.g., piezometers, pushpoint samplers) for instantaneous concentrations and (2) tools that passively collect samples over time (e.g., peepers, seepage meters, and PDSs) for more integrated concentrations or contaminant mass.

4.2 Evaluating Biota Exposure and Effects

Baseline ERAs of other ecosystems typically employ evaluations of exposure and effects to provide multiple lines of evidence for characterizing risks. The methods typically employed in evaluating exposure and effects to benthic biota can be readily extended to transition zone biota exposed to contaminated ground-water discharges. These methods include benthic community analyses, toxicity testing, and bioaccumulation evaluations. In selecting these methods to evaluate exposure and effects to transition zone biota, the risk assessor must consider the same issues that are typically addressed during benthic ecosystem risk assessments. These issues include, but may not be limited to, the use of reference sites to address natural variability and background conditions (U.S. EPA 1994d), confounding factors that could affect toxicity results, toxicity testing using media collected along contamination gradients in order to develop dose-response relationships, and uncertainties associated with many of the input parameters of uptake models. These issues are typically addressed during the problem formulation and study design portions of ERA development (Steps 3 and 4, respectively, of the Superfund ERA process).

Community analysis of transition zone organisms can be used to identify differences in community structure, biomass, species richness and density, relative abundance, and other parameters (U.S. EPA 1994c), and a variety of methods are available for sampling and evaluating transition zone biota (i.e., Hendricks 1996; Williams 1999). However, evaluating alterations in transition zone communities is challenging, and shares exactly the same issues and considerations as benthic community analyses or other field studies. These issues include natural variability (e.g., associated with ground-water discharge/recharge), the need for concurrent community analyses at appropriate reference sites (see Barbour et al. 1999), and the overarching need for synoptic sampling of exposures and effects.

Toxicity testing and bioaccumulation evaluations have been used at several sites to evaluate the effects of ground-water contamination on transition zone biota. Toxicity testing, which involves the exposure of organisms to contaminated media, provides direct evidence of contaminant effects on transition zone biota (U.S. EPA 1994e). A wide variety of toxicity tests have been developed for use in ecological risk assessments (U.S. EPA 1994b), and many of these may be directly applicable to evaluating contaminant effects on transition zone biota. While these types of studies are often conducted in the laboratory using media collected from the site, *in situ* studies have also been used and may be preferable because they provide more realistic exposures than do laboratory studies (U.S. EPA 1994e; Greenberg et al. 2002; Burton et al. 2005).

Bioaccumulation evaluations examine the uptake of contaminants by exposed biota and can be used to infer potential effects to transition zone biota when concentrations exceed tissue levels considered adverse to the organisms or their predators. Bioaccumulation may be measured by (1) tissue analysis of indigenous biota, (2) analysis of cultured test organisms (e.g., fish, macroinvertebrates) exposed *in situ* (US EPA 2004), (3) the use of SPMDs, and (4) the use of contaminant-uptake models. Tissue analysis provides a direct estimate of contaminant uptake and bioaccumulation under site-specific conditions. Semipermeable membrane devices may also provide a site-specific estimate of passive uptake and bioaccumulation. However, because SPMDs serve as surrogates for biota and involve no sampling or analysis of biota, their use for estimating bioaccumulation should be approached with caution. Unless a quantitative relationship has been established between the bioaccumulation estimated by the SPMD and that measured in biota exposed at the site, the use of SPMDs is not recommended for evaluating bioaccumulation. These devices may, however, be useful for delineating areas of contaminated ground-water discharge (as in Step 2 of the transition zone problem formulation framework) or monitoring these areas (Huckins et al. 1993). Because contaminants partition among water, sediment, and organisms (recall that partitioning will have been evaluated during problem formulation and CSM development), sediment analysis may be necessary to interpret bioaccumulation results for decision-making.

While there currently are no examples of quantitative contaminant uptake models for transition zone biota, existing approaches used to estimate contaminant uptake by aquatic biota may be applicable for use in transition zone ecosystems. For aquatic biota, contaminant uptake models employing laboratory-derived BCFs or field-derived bioaccumulation factors (BAFs) are commonly used to estimate biota tissue concentrations from contaminant concentrations measured in aquatic media (e.g., see Suter et al. 2000). While such models may be used for estimating tissue concentrations in transition zone biota, the risk assessor should address many of the typical modeling issues (such as nonlinearity between BCFs and ambient contaminant concentrations when selecting a BCF; and the potential for deviations from equilibrium assumptions) in the interpretation of model results.

4.3 Characterizing Risks

Ecological risks to the transition zone are characterized after the collection and analysis of physical, chemical, and ecological data have been completed (Figure 4). The risks can be characterized using the lines-of-evidence approach commonly used in ecological risk assessments (U.S. EPA 1997, 1998). The characterization includes uncertainty analysis to assist in risk management. Incorporating the transition zone leads to improved decision-making in the overall ERA by reducing uncertainty in the conclusions of which receptors/assessment endpoints are significantly impacted, determining which stressors dominate, and from which compartments (e.g., surface-water, bedded sediments, upwelling ground-water) those stressors originate.

5. Summary

The transition zone represents a unique and important ecosystem that exists between surface-water and the underlying ground-water, receiving water from both of these sources. Biota inhabiting, or otherwise dependent on, the transition zone may be adversely impacted by contaminated ground-water discharging through the transition zone into overlying surface-waters. ERAs addressing contaminated ground-water discharge to surface-waters typically have not evaluated potential contaminant effects to biota in the transition zone. However, numerous hydrogeological and ecological methods and tools are available for delineating ground-water discharge areas in a rapid and cost-effective manner, and for evaluating the effects of contaminant exposure on transition zone biota. These tools and approaches, which are commonly used in hydrogeological and ecological investigations, can be readily employed within the existing EPA framework for conducting screening- and baseline-level ERAs in Superfund (U.S. EPA 1997) and satisfy the requirement to identify and characterize the current and potential threats to the environment from a hazardous substance release.

6. Glossary

Abiotic: Characterized by absence of life; abiotic materials include the nonliving portions of environmental media (e.g., water, air, soil, sediment), including light, temperature, pH, humidity, current velocity, and other physical and chemical parameters. Abiotic chemical reactions are not biologically mediated (i.e., do not involve microbes).

Acute: Having a sudden onset or lasting a short time. An acute stimulus to a contaminant is severe enough to induce a rapid response. With regard to ground-water contamination, the term acute can be used to define either exposure to a chemical (short term) or the response to such an exposure (effect).

Aquifer: A body of geological materials such as sand and gravel or sandstone, that is sufficiently permeable to transmit ground-water and yield economically significant quantities of water to wells or springs

Assessment Endpoint: An explicit expression of the environmental value that is to be protected, such as specific ecological processes, or populations/communities of organisms to be protected (e.g., a sustainable population of insect larvae important as fish food)

Baseline Ecological Risk Assessment: An ecological risk assessment that evaluates the exposure and effects of a contaminant to ecological resources under site-specific exposure scenarios and using site-specific physical, chemical, and biological data.

Benchmark Value: In ecological risk assessment, a media-specific environmental concentration or a receptor-specific dose concentration that represents a threshold for adverse ecological effects (a maximum "safe" chemical concentration or dose). Media or dose concentrations at or below a benchmark value are considered unlikely to cause adverse ecological effects.

Benthos: The community of organisms (plants, invertebrates, and vertebrates) dwelling on the bottom of a body of surface-water (e.g., pond, lake, stream, river, wetland, estuary, ocean).

Bioaccumulation: The process by which chemicals are taken up and incorporated by an organism either directly from exposure to a contaminated medium or by consumption of food or water containing the contaminant.

Bioaccumulation Factor (BAF): The ratio of the concentration of a contaminant in an organism to the concentration in the ambient environment at steady state, where the organisms can take in the contaminant through ingestion with its food and water as well as through direct contact.

Bioconcentration: The process by which there is net accumulation of a chemical directly from an exposure medium into an organism.

Bioconcentration Factor (BCF): The ratio of the concentration of a contaminant in an organism to the concentration in the exposure medium, where the organisms can take in the contaminant through direct contact with the medium.

Biodegradation: The process by which chemical compounds are degraded into more elementary compounds by the action of living organisms; usually refers to microorganisms such as bacteria.

Biomass: Any quantitative estimate of the total mass of organisms comprising all or part of a population or any other specified unit, or within a given area at a given time; typically measured as a volume or mass (weight).

Biome: A biogeographical region or formation; a major regional ecological community characterized by distinctive life forms and principal plant or animal species.

Biotic: The living portion of the environment; pertaining to life or living organisms; caused by, produced by, or comprising living organisms.

Chronic: Involving a stimulus that is lingering or continues for a long time; often signifies periods of time associated with the reproductive life cycle of a species. Can be used to define either exposure to a chemical or the response to such an exposure (effect). Chronic exposures to chemicals typically induce a biological response of relatively slow progress and long duration.

Community: Any group of organisms comprising a number of different species that co-occur in the same habitat or area and interact through trophic and spatial relationships.

Community Analysis: An analysis of a community within a specified location and time. Community analyses may focus on the number of different species present, the types of species present, or the relative abundance of the species that are present in the community.

Community Structure: Refers to the species composition and abundance and the relationships between species in a community.

Conceptual Site Model: Describes a series of working hypotheses of how a stressor (chemical contaminant) might reach and affect a biological assessment endpoint; describes the assessment endpoint potentially at risk from exposure to a chemical, the exposure scenario for the receptor, and the relationship between the assessment and measurement endpoints and the exposure scenarios.

Diffusion: The process by which both ionic and molecular species dissolved in water move from areas of higher concentration to areas of lower concentration.

DNAPL: dissolved non-aqueous phase liquid

Downwelling: The movement of surface-water down into or through the underlying porous media (e.g., recharge to ground-water).

Ecohydrology: An emerging discipline linking ecology with hydrology through the entire water cycle over scales ranging from plant community relationships with ground-water to watershed-level processes.

Ecological Risk Assessment: The process that evaluates the likelihood that adverse ecological effects may occur as a result of exposure to one or more stressors.

Ecosystem: The biotic and abiotic environment within a specified location and time, including the physical, chemical, and biological relationships among the biotic and abiotic components.

Ecotone: The boundary or transition zone between adjacent communities or biomes.

Electrical Conductivity: A measure of the ability of a solution to carry an electrical current. Conductivity is dependent on the total concentration of ions dissolved in the water

Environmental Value: (See Assessment Endpoint). Environmental values include specific ecological processes or populations/communities of organisms to be protected (e.g., a sustainable population of insect larvae important as fish food).

Epifauna: Biota that live on the surface of sediment, as distinguished from infauna, which live in the sediment.

Exposure Pathway: The course a chemical or physical agent takes from a source to an exposed organism. Each exposure pathway includes a source or release from a source, an exposure point, and an exposure route (including respiration [e.g. via gills], ingestion, etc.). If the exposure point location differs from the source, transport/exposure media (i.e., air, water) are also included.

Exposure Point Concentration: The concentration of a contaminant at an exposure point.

Food Web: The pattern of interconnected energy (food) transport among plants and animals in an ecosystem, where energy is transferred from plants to herbivores and then to carnivores by feeding.

Ground-Water Discharge Zone: An area where ground-water exits the subsurface as a spring or a seep, as baseflow into a stream, or directly into an overlying surface-water body (pond, lake, ocean).

Ground-Water/Surface-Water Interface: The boundary between ground-water and surface-water that occurs in the substrate beneath the surface-water body. It is usually defined by examining and mapping interstitial water quality to determine the origin of the water. It may be very diffuse and dynamic and difficult to define (compare with: Transition Zone).

Habitat: The local environment occupied by an organism with characteristics beneficial to the organism. The habitat may be used only during a certain life stage or season

Hydraulic Conductivity: The capacity of a rock to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic Gradient: The change of hydraulic head per unit of distance in a given direction.

Hydraulic head: The height of the free surface of a body of water above a given point beneath the surface.

Hypolentic Zone: The zone of ground-water and surface-water mixing that occurs in the sediments beneath a lake or wetlands (not beneath moving waters, see Hyporheic Zone).

Hyporheic Zone: Latticework of underground habitats through the sediments associated with the interstitial waters in the substrate beneath and adjacent to moving surface-waters. The hyporheos is the community of organisms adapted to living in this zone. The zone is defined based on biological, hydrological, and chemical characteristics.

Infauna: Biota that live within or burrow through the substrate (sediment), as distinguished from epifauna, which live upon the substrate

Infiltration: Process by which water moves from the earth’s surface or from surface-water down into the ground-water system.

***In Situ*:** Refers to a condition or investigation (such as a toxicity test) in the environment (in the field at a site).

Interstitial Water: The water filling the spaces between grains of sediment. Often used interchangeably with “pore water.” The term indicates only the presence of water, not its origin.

Macroinvertebrate: An invertebrate animal large enough to be seen without magnification and retained by a 0.595-mm (U.S. #30) screen.

Measurement Endpoint: A measurable ecological characteristic that is related to the valued characteristic chosen as the assessment endpoint; often expressed as the statistical or arithmetic summaries of observations that make up the measurement.

Meiofauna: The small biota (<1 mm diameter) that inhabit the interstitial spaces in sediment.

Natural Attenuation: The natural dilution, dispersion, (bio)degradation, irreversible sorption, and/or radioactive decay of contaminants in soils and ground-water.

Periphyton: Attached microflora growing on the bottom of a water body, or on other submerged substrates, including higher plants.

Permeability: The capacity of a rock for transmitting a fluid; a measure of the relative ease with which a porous medium can transmit a liquid.

Piezometer: A small-diameter, nonpumping tube, pipe, or well used to measure the elevation of the water table or potentiometric surface. A piezometer may also be used to collect ground-water samples.

Pore Water: The water filling the spaces between grains of sediment. Often used interchangeably with “interstitial water.”

Potentiometric Surface: A surface that represents the level to which water will rise in tightly cased wells. The water table is the potentiometric surface of an unconfined, or the uppermost, aquifer.

Problem Formulation: Problem formulation establishes the goals, breadth, and focus for an assessment. In a baseline ecological risk assessment, problem formulation establishes the assessment endpoints, identifies exposure pathways and routes, and develops a conceptual site model with working hypotheses and questions that the site investigation will address.

Productivity: (1) The rate of formation of new tissue or organisms, or energy use, by one or more organisms. (2) Capacity or ability of an environmental unit to produce organic material.
(3) Recruitment ability of a population from natural reproduction.

Refuge (refugia): An area to which an organism may escape to avoid a physical (e.g., temperature, water current), chemical (e.g., low dissolved oxygen, a high contaminant concentration), or biologic stressor (e.g., a predator).

Risk: The expected frequency or probability of undesirable effects resulting from known or expected exposure to a contaminant.

Risk Characterization: A phase of an ecological risk assessment in which the results of the assessment are integrated to evaluate the likelihood of adverse ecological effects associated with exposure to a contaminant.

Risk Question: Questions developed during the problem formulation phase of a baseline risk assessment, about the relationships among the assessment endpoints, exposure pathways, and potential effects of the exposure. These questions provide the basis for developing the risk assessment study design and the subsequent evaluation of the results.

Screening Ecological Risk Assessment: An ecological risk assessment that evaluates the potential for adverse ecological effects to ecological resources under very conservative site-specific exposure scenarios (e.g., maximum documented exposure concentrations) and using screening benchmark values.

Species Richness: The absolute number of species in a community.

Stressor: Any physical, chemical, or biological entity that can induce an adverse ecological response (e.g., reduced reproduction, increased mortality, habitat avoidance).

Surrogate Species: A species selected to be representative of an assessment endpoint and on which a risk characterization will focus.

Total Organic Carbon (TOC): Estimated concentration of the sum of all organic carbon compounds in a water or sediment sample by various methods. It can influence bioavailability because some contaminants adsorb to organic carbon.

Toxicity Test: An evaluation of the toxicity of a chemical or other test material (environmental media) conducted by exposing a test organism to a specific level of the chemical or environmental media and measuring the degree of response (mortality, reduced growth, reduced egg production) associated with the specific exposure level.

Transition Zone: The zone of transition from a ground-water dominated system to a surface-water dominated system. It includes, but is not limited to the zone where the ground-water and surface-water mix as well as any Ground-Water/Surface-Water Interface that may be present.

Unconfined Aquifer: An aquifer in which there are no confining beds between the zone of saturation and the surface.

Upwelling: The movement of water in an underlying porous medium up into the surface-water (e.g., ground-water discharge).

Water table: The elevation of the water surface in a well screened in the uppermost zone of saturation (ground-water), i.e., in an unconfined aquifer.

7. References

Adamus, P.R. 1995. *Bioindicators for Assessing Ecological Integrity of Prairie Wetlands*. EPA/600/R-96/082.
U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Ore. www.epa.gov/owow/wetlands/wqual/ppaindex.html.

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling. 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. www.epa.gov/OWOW/monitoring/techmon.html

Boulton, A. 2000. The subsurface macrofauna. In: Streams and Groundwater. (Eds.: J. Jones, J. and P. Mulholland). Academic Press, San Diego. pp. 337-361.

Burton G.A. Jr, M.S. Greenberg, C.D. Rowland, C.A. Irvine, D.R. Lavoie, J.A. Brooker, L. Moore, D.F.N. Raymer, and R.A. McWilliam . 2005. In situ exposures using caged organisms: a multi-compartment approach to detect aquatic toxicity and bioaccumulation. Environmental Pollution 134:133-144.

Carls, M.G., R.E. Thomas, M.R. Lilly and S.D. Rice. 2003. *Mechanism for transport of oil-contaminated groundwater into pink salmon redds*. Marine Ecology Progress Series 248:245-255.

Conant Jr., B., 2000. Ground water plume behavior near the ground water/surface water interface of a river. In: *Proceedings of the Ground Water/Surface Water Interactions Workshop*, Denver Colorado, January 26-28, 1999. EPA/542/R-00/007, p. 23-30.

Conant, Jr., B. 2001. *A PCE Plume Discharging to a River: Investigations of Flux, Geochemistry, and Biodegradation in the Streambed*, Ph.D. Thesis. Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, Canada. 543 pp. www.science.uwaterloo.ca/earth/theses/abstracts/conant_brewst er.html.

Conant, Jr., B. 2004. Delineating and Quantifying Ground Water Discharge Zones Using Streambed Temperatures. Ground Water 42(2):243-257.

Conant, Jr., B., J.A. Cherry, and R.W. Gillham. 2004. *A PCE Groundwater Plume Discharging to a River: Influence of the Streambed and Near-River Zone on Contaminant Distributions*. Journal of Contaminant Hydrology 73:249-279.

Dahm, C.N., and H.M. Valett. 1996. Hyporheic Zones. In: F.R. Hauer and G.A. Lamberti (eds.), *Methods in Stream Ecology*. Academic Press, San Diego. pp. 107-119.

Danielopol, D.L, Griebler, C., Gunatilaka, A., and J. Notenboom, 2003. Present state and future prospects for groundwater ecosystems. *Environmental Conservation* 30 (2): 104–130

Duff, J.H., F. Murphy, C.C. Fuller, and F.J. Triska. 1998. *A Mini Drivepoint Sampler for Measuring Pore Water Solute Concentrations in the Hyporheic Zone of Sand Bottom Streams*. Limnology and Oceanography 43(6):1378-1383.

Fenchel, T., G.M. King, and T.H. Blackburn. 1988. *Bacterial Biogeochemistry: The Ecophysiology of Mineral Cycling*, 2nd Ed. Academic Press, San Diego. 307 pp.

Fetter, C.W. 2000. Applied Hydrogeology, 4th Ed. Prentice Hall Inc., Upper Saddle River, New Jersey. 598 pp.

Ford, R. G. The Impact of Ground Water-Surface Water Interactions on Contaminant Transport with Application to an Arsenic Contaminated Site, EPA Environmental Research Brief, EPA/600/S-05/002. Cincinnati, OH: U.S. Environmental Protection Agency, 2005. http://www.epa.gov/ada/download/briefs/epa_600_s05_002.pdf

Geist, D.R., and D.D. Dauble. 1998a. *Redd Site Selection and Spawning Habitat Use by Fall Chinook Salmon: the Importance of Geomorphic Features in Large Rivers*. Environmental Management 22:655-669. [Check text entries.]

Gibert, J., D.L. Danielopol, and J.A. Stanford. 1994. *Groundwater Ecology*. Academic Press, San Diego.

Greenberg, M.S., G.A. Burton, Jr., and C.D. Rowland. 2002. *Optimizing Interpretation of in Situ Effects of Riverine Pollutants: Impacts of Upwelling and Downwelling*. Environmental Toxicology and Chemistry 21(2):289-297.

Grimm, N.B. 1996. Surface-Subsurface Interactions in Streams. In:
F.F. Hauer and G.A. Lamberti (eds.), *Methods in Stream Ecology*. Academic Press, San Diego. pp. 625-646.

Hayashi, M., and D.O. Rosenberry. 2002. Effects of Groundwater Exchange on the Hydrology and Ecology of Surface Water. Ground Water 40(3):309-316.

Hendricks, S.P. 1996. *Bacterial Biomass, Activity, and Production within the Hyporheic Zone of a North-Temperate Stream*. Archiv für Hydrobiologie 135:467-487.

Henry, M.A. 2000. MHE Push Point Sampling Tools, Appendix D. In: *Proceedings of the Ground Water/Surface Water Interactions Workshop.* EPA/542/R-00/007. pp. 191-200. Ewww.epa.gov/tio/tsp/issue.htm#GWF and www-personal. engin.umich.edu/~markhen/index.htm.

Hesslein, R.H. 1976. *An in-Situ Sampler for Close Interval Pore Water Studies*. Limnology and Oceanography 21:912-914.

Huckins, J.N., G.K. Manuweera, J.D. Petty, D. Mackay, and J.A. Lebo. 1993. *Lipid-Containing Semipermeable Membrane Devices for Monitoring Organic Contaminants in Water*. Environmental Science and Technology 27:2489-2496.

Hughes, B.M., R.D. McClellan, and R.W. Gillham. 1992. Application of Soil-Gas Sampling Technology to the Studies of Trichloroethylene Vapor Transport in the Unsaturated Zone. In: Lesage, S. and R.E. Jackson (eds.), *Ground Water Contamination and Analysis at Waste Sites*. Marcel Dekker, Inc., New York. pp. 121-146.

Krest, J.M and J. W. Harvey. 2003. *Using natural distributions of short-lived radium isotopes to quantify groundwater discharge and recharge.* Limnology and Oceanography 48(1):290-298.

Lee, D.R. 1977. *A Device for Measuring Seepage Flux in Lakes and Estuaries*. Limnology and Oceanography 21(2):140-147.

Lee, D.R., and J.A. Cherry. 1978. A field exercise on groundwater flow using seepage meters and mini-piezometers. *Journal of Geological Education* 27: 6-10.

Lee, D.R. 1985. Method for Locating Sediment Anomalies in Lake Beds That Can Be Caused by Ground Water Flow. Journal of Hydrology 79:187-193.

Lendvay, J.M., W.A. Sauck, M.L. McCormick, M.J. Barcelona, D.H. Kampbell, J.T. Wilson, and P. Adriaens. 1998. *Geophysical Characterization, Redox Zonation, and Contaminant Distribution at a Groundwater/Surface Water Interface*. Water Resources Research 34(12):3545-3559.

Lorah, M.M., L.D. Olsen, B.L. Smith, W.B. Johnson, and W.B. Fleck. 1997. *Natural Attenuation of Chlorinated Volatile Organic Compounds in a Freshwater Tidal Wetland, Aberdeen Proving Ground, Maryland.* U.S. Geologic Survey Water Resources Investigations Report 97-4171. U.S. Geologic Survey, Baltimore, Md.

Malard, F., S. Plenet, and J. Gilbert. 1996. *The Use of Invertebrates in Ground Water Monitoring: A Rising Research Field.* Groundwater Monitoring & Remediation 16(1):103-113.

Mayer, L.M. 1976. *Chemical Water Sampling in Lakes and Sediments with Dialysis Bags.* Limnology and Oceanography 21:912-914.

MDEQ (Michigan Dept. of Environmental Quality) 2006Technical Memorandum: Bendix Superfund Site, , in review

Montgomery, J.R., C.F. Zimmerman, and M.T. Price. 1979. *The Collection, Analysis, and Variation of Nutrients in Estuarine Pore Water.* Estuarine and Coastal Marine Science 9:203-214.

Morse, J.W. 1995. *Dynamics of Trace Metal Interactions with Authigenic Sulfide Minerals in Anoxic Sediments.* In Metal Contaminated Aquatic Sediments. H.E. Allen, editor. Ann Arbor Press. Pgs. 175-185.

Pardue, J.H. and W. H. Patrick, Jr. 1995. *Changes in Metal Speciation Following Alteration of Sediment Redox Status*. In Metal Contaminated Aquatic Sediments. H.E. Allen, editor. Ann Arbor Press. Pgs. 175-185.

Pitkin, S.E., J.A. Cherry, R.A. Ingelton, and M. Broholm. 1999. Field demonstrations using the Waterloo ground-water profiler. *Ground Water Monitoring and Remediation* 19, no. 2: 122-131.

Power, G., R.S. Brown, and J.G. Imhof. 1999. *Groundwater and Fish — Insights from Northern North America*. Hydrological Processes 13:401-422.

Savoie, J. G., LeBlanc, D. R., Blackwood, D. S., McCobb, T. D., Rendigs, R. R., and Clifford, S., 2000, Delineation of discharge areas of two contaminant plumes by use of diffusion samplers, Johns Pond, Cape Cod, Massachusetts, 1998: Northborough, Massachusetts, U.S. Geological Survey, *U.S. Geological Survey Water-Resources Investigations Report 00-4017*.

Smock, L, J. Gladden, J. Riekenberg, L. Smith, and C. Black. 1992. Lotic macroinvertebrate production in three dimensions: channel surface, hyporheic, and floodplain environments. Ecol 73: 876-886.

Stanford, J.A., and J.V. Ward. 1993. *An Ecosystem Perspective of Alluvial Rivers: Connectivity and the Hyporheic Corridor.*
J.N. Am. Benthol. Soc. 12:48-60.

Storey, R.G., Fulthorpe, R.R., and D.D. Williams, 1999. Perspectives and predictions on the microbial ecology of the hyporheic zone. *Freshwater Biology*, v 41, no 1., 119-130.

Suter, G.W., R.A. Efroymson, B.E. Sample, and D.S. Jones. 2000. *Ecological Risk Assessment for Contaminated Sites*. Lewis Publishers, CRC Press LLC, Boca Raton, Fla.

Tobias, C.R., J.W. Harvey, and I.C. Anderson. 2001. *Quantifying Groundwater Discharge through Fringing Wetlands to Estuaries: Seasonal Variability, Methods Comparison, and*

Implications for Wetland-estuary Exchange. Limnology and Oceanography. 46(3) 604-615.

U.S. EPA. 1992. *Framework for Ecological Risk Assessment*. Washington, D.C. Risk Assessment Forum. EPA/630/R-92/001.

U.S. EPA. 1994a. *Role of the Ecological Risk Assessment in the Baseline Risk Assessment.* OSWER Directive No. 9285.7-17. Office of Solid Waste and Emergency Response, Washington, D.C. Aug. 12.

U.S. EPA. 1994b. *Catalogue of Standard Toxicity Tests for Ecological Risk Assessment*. ECO Update, Interim Bulletin, Volume 2, Number 2. Washington, D.C. Office of Emergency and Remedial Response, Hazardous Site Evaluation Division. Publication 93450-05I. EPA/540/F-94/013. NTIS PB94-963304. www.epa.gov/oerrpage/superfund/ programs/risk/ecoup/v2no2.pdf.

U.S. EPA. 1994c. *Field Studies for Ecological Risk Assessment*. ECO Update, Interim Bulletin, Volume 2, Number 3. Washington, D.C. Office of Emergency and Remedial Response, Hazardous Site Evaluation Division. Publication 9345.05I. EPA/540/F-94/014. NTIS PB94-963305. www.epa.gov/oerrpage/superfund/programs/ risk/ecoup/v2no3.pdf.

U.S. EPA. 1994d. *Selecting and Using Reference Information in Superfund Risk Assessments.* ECO Update, Interim Bulletin, Volume 2, Number 4. Washington, D.C. Office of Emergency and Remedial Response, Hazardous Site Evaluation Division. Publication 9345.10. EPA/540/F-94/050. NTIS PB94-963319.

U.S. EPA. 1994e. *Using Toxicity Tests in Ecological Risk Assessment*. ECO Update, Interim Bulletin, Volume 2, Number 1. Washington, D.C. Office of Emergency and Remedial Response, Hazardous Site Evaluation Division. Publication 9345.05I. EPA/540/F-94/012. NTIS PB94-963303. www.epa.gov/oerrpage/ superfund/programs/risk/ ecoup/v2no1.pdf.

U.S. EPA. 1997. *Ecological Risk Assessment Guidance for Superfund, Process for Designing and Conducting Ecological Risk Assessments, Interim Final*. EPA 540-R-97-006. OSWER Directive No. 9285.7-25. www.epa.gov/superfund/programs/risk/ ecorisk/ecorisk.htm..

U.S. EPA. 1998. *Guidelines for Ecological Risk Assessment*, *Final*. EPA/630/R95/002F. Risk Assessment Forum, Washington,
D.C. Published May 14. *Federal Register* 63(93):26846-26924).
www.epa.gov/ncea/ecorsk.htm.

U. S. Environmental Protection Agency (EPA). 2000. Proceedings of the Ground Water/Surface Water Interactions Workshop. Office of Solid Waste and Emergency Response: Washington, DC, EPA 542/R-00/007. http://www.clu-in.org/s.focus/c/pub/i/600/

U.S. EPA. 2001a. *The Role of Screening-Level Risk Assessments and Refining Contaminants of Concern in Baseline Ecological Risk Assessments*. ECO Update, Intermittent Bulletin. Washington, D.C. Office of Solid Waste and Emergency Response. Publication 9345.0-14. EPA 540/F-01/014. June.

U.S. EPA. 2001b. Methodsfor Collection, Storage and Manipulation of Sediments for Chemical and Toxicological Analyses: Technical Manual. Office of Water. EPA-823-B-01-002.
USGS.
Http://geopubs.wr.usgs.gov/open-file/of02-367/of02-367.pdf

U.S. EPA. 2002a. *National Recommended Water Quality Criteria: 2002.* EPA-822-R-02-047. Office of Water, Office of Science and Technology, Washington, D.C. Nov.

U.S. EPA. 2002b. *Ground Water Sampling Guidelines for Superfund and RCRA Project Managers*. EPA 542-S-02-001. May. www.epa.gov/tio/tsp/issue.htm.

U.S. EPA. 2003. *A Compendium of Chemical, Physical and Biological Methods for Assessing and Monitoring the Remediation of Contaminated Sediment Sites*. EPA 600-R-04-108.

US EPA. 2004. *Five-Year Review Report for the Sangamo Weston/Twelve Mile Creek/Lake*

Hartwell PCB Contamination Superfund Site – Operable Unit Two, Pickens, South Carolina. Executive Summary, 21 pgs.
USGS. Http://ma.water.usgs.gov/publications/wrir/wri024186/report.htm.

Valiela, I., J. Costa, K. Foreman, J.M. Teal, B. Howes, and D. Aubrey. 1990. *Transport of Ground Water-borne Nutrients from Watersheds and their Effects on Coastal Waters.* Biogeochemistry 10, 177-197.

Vroblesky, D.A., L.C. Rhodes, J.F. Robertson, and J.A. Harrigan. 1996. *Locating VOC Contamination in a Fractured-Rock Aquifer at the Ground Water/Surface Water Interface Using Passive Vapor Collectors.* Ground Water 34(2):223-230.

Vroblesky, D.A., and W.T. Hyde. 1997. *Diffusion Samplers as an Inexpensive Approach to Monitoring VOCs in Ground Water.* Ground Water Monitoring and Remediation 16(3):177-184.

Vroblesky, D.A., C.T. Nietch, J.F. Robertson, P.M. Bradley, J. Coates, and J.T. Morris. 1999. *Natural Attenuation Potential of Chlorinated Volatile Organic Compounds in Ground Water, TNX Floodplain, Savannah River Site, South Carolina*. U.S. Geological Survey. Water Resources Investigations Report 99-4071. 43 pp.

Washington State Dept. of Ecology. Http://www.ecy.wa.gov/pubs/0110041.pdf.

Wassen, M.J., and A.P. Grootjans. 1996. Ecohydrology: An Interdisciplinary approach for wetland management and restoration. Vegetatio 126, 1-4.

Wetzel, R.G. 2001. *Limnology: Lake and River Ecosystems*, 3rd Ed. Academic Press, San Diego. 1006 pp.

White, D.S. 1993. Perspectives on defining and delineating hyporheic zones. *Journal of the North American Benthological Society* 12, no. 1: 61-69.

Williams, D.D. 1999. Field Technology and Ecological Characterisation of the Hyporheic Zone. In: Proceedings of the Ground Water/Surface Water Interactions WorkshopDenver Colorado, January 26-28, 1999. EPA/542/R-00/007, p. 39-44.

Winter, T.C., J.W. LaBaugh, and D.O. Rosenberry. 1988. The Design and Use of a Hydraulic Potentiomanaometer for Direct Measurement of Differences in Hydraulic Head between Groundwater and Surface Water. Limnology and Oceanography 33(5):1209-1214.

Winter, T. C., Harvey, J. W., Franke, O. L., Alley, W. M. 1998. Ground water and surface water: a single resource. U.S. Geological Survey Circular 1139, 79 pp., http://water.usgs.gov/pubs/circ/circ1139/pdf/circ1139.pdf

Woessner, W.W. 2000. *Stream and Fluvial Plain Ground Water Interactions: Rescaling Hydrogeologic Thought*. Ground Water 38(3):423-429.

Zimmerman, C. F., M.T. Price, and J.R. Montgomery. 1978. *A Comparison of Ceramic and Teflon in Situ Samplers for Nutrient Pore Water Determinations*. Estuarine and Coastal Marine Science 7:93-97.

Zimmerman, M.J., Massey, A.J., Campo, K.W., 2005, Pushpoint Sampling for Defining Spatial and Temporal Variations in Contaminant Concentrations in Sediment Pore Water near the Ground Water/Surface Water Interface: U.S. Geological Survey Scientific Investigations Report 2005-5036, 70 p.

EPA
United States
Environmental Protection
Agency

EPA/100/K-09/003 | March 2009
www.epa.gov/crem

Guidance on the Development, Evaluation, and Application of Environmental Models

Office of the Science Advisor
Council for Regulatory Environmental Modeling

EPA/100/K-09/003
March 2009

Office of the Science Advisor

Guidance on the Development, Evaluation, and Application of Environmental Models

Council for Regulatory Environmental Modeling
U.S. Environmental Protection Agency
Washington, DC 20460

Preface

This *Guidance on the Development, Evaluation, and Application of Environmental Models* was prepared in response to a request by the U.S. Environmental Protection Agency (EPA) Administrator that EPA's Council for Regulatory Environmental Modeling (CREM) help continue to strengthen the Agency's development, evaluation, and use of models (http://www.epa.gov/osp/crem/library/whitman.PDF).

A draft version of this document (http://cfpub.epa.gov/crem/crem_sab.cfm) was reviewed by an independent panel of experts established by EPA's Science Advisory Board and revised by CREM in response to the panel's comments.

This final document is available in printed and electronic form. The electronic version provides direct links to the references identified in the document.

Disclaimer

This document provides guidance to those who develop, evaluate, and apply environmental models. It does not impose legally binding requirements; depending on the circumstances, it may not apply to a particular situation. The U.S. Environmental Protection Agency (EPA) retains the discretion to adopt, on a case-by-case basis, approaches that differ from this guidance.

Authors, Contributors, and Reviewers

This document was developed under the leadership of EPA's Council for Regulatory Environmental Modeling. A number of people representing EPA's core, program, and regional offices helped write and review it.

<u>PRINCIPAL AUTHORS:</u>

Council for Regulatory Environmental Modeling Staff:
Noha Gaber, Gary Foley, Pasky Pascual, Neil Stiber, Elsie Sunderland

EPA Region 10:
Ben Cope

Office of Environmental Information:
Annett Nold (deceased)

Office of Solid Waste and Emergency Response:
Zubair Saleem

<u>CONTRIBUTORS AND INTERNAL REVIEWERS:</u>

EPA Core Offices:
Office of Research and Development:
Justin Babendreier, Thomas Barnwell (retired), Ed Bender, Lawrence Burns (retired), Gary Foley, Kathryn Gallagher, Kenneth Galluppi, Gerry Laniak, Haluk Ozkaynak, Kenneth Schere, Subhas Sikdar, Eric Weber, Joe Williams

Office of Environmental Information:
Ming Chang, Reggie Cheatham, Evangeline Cummings, Linda Kirkland, Nancy Wentworth

Office of General Counsel:
James Nelson (retired), Barbara Pace, Quoc Nguyen, Manisha Patel, Carol Ann Sicilano

Science Advisory Board:
Jack Kooyoomjian

EPA Program Offices:
Office of Air and Radiation:
Tyler Fox, John Irwin (retired), Joe Tikvart, Richard (Chet) Wayland, Jason West

Office of Prevention, Pesticides and Toxic Substances:
Lynn Delpire, Alan Dixon, Wen-Hsiung Lee, David Miller, Vince Nabholz, Steve Nako, Neil Patel, Randolph Perfetti (retired), Scott Prothero, Donald Rodier

Office of Solid Waste and Emergency Response:
Peter Grevatt, Lee Hofmann, Stephen Kroner (retired), Larry Zaragoza

Office of Water:
Jim Carleton, Sharon E. Hayes, Marjorie Wellman, Denise Keehner, Lauren Wisniewski, Lisa McGuire, Mike Messner, James F. Pendergast

EPA Regional Offices:
Region 1:
Brian Hennessey, Michael Kenyon

Region 2:
Kevin Bricke, Rosella O'Connor, Richard Winfield

Region 3:
Alan Cimorelli

Region 4:
Nancy Bethune, Brenda Johnson, Tim Wool

Region 5:
Bertram Frey, Arthur Lubin, Randy Robinson, Stephen Roy, Mary White

Region 6:
James Yarborough

Region 7:
Bret Anderson

Region 10:
David Frank (retired), John Yearsley (retired)

Contents

APPENDICES

Executive Summary

In pursuing its mission to protect human health and to safeguard the natural environment, the U.S. Environmental Protection Agency often relies on environmental models. In this guidance, a model is defined as a "*simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system."*

This guidance provides recommendations for the effective development, evaluation, and use of models in environmental decision making once an environmental issue has been identified. These recommendations are drawn from Agency white papers, EPA Science Advisory Board reports, the National Research Council's *Models in Environmental Regulatory Decision Making*, and peer-reviewed literature. For organizational simplicity, the recommendations are categorized into three sections: *model development*, *model evaluation*, and *model application*.

Model development can be viewed as a process with three main steps: (a) specify the environmental problem (or set of issues) the model is intended to address and develop the conceptual model, (b) evaluate or develop the model framework (develop the mathematical model), and (c) parameterize the model to develop the application tool.

Model evaluation is the process for generating information over the life cycle of the project that helps determine whether a model and its analytical results are of sufficient quality to serve as the basis for a decision. Model quality is an attribute that is meaningful only within the context of a specific model application. In simple terms, model evaluation provides information to help answer the following questions: (a) How have the principles of sound science been addressed during model development? (b) How is the choice of model supported by the quantity and quality of available data? (c) How closely does the model approximate the real system of interest? (d) How well does the model perform the specified task while meeting the objectives set by quality assurance project planning?

Model application (i.e., model-based decision making) is strengthened when the science underlying the model is transparent. The elements of transparency emphasized in this guidance are (a) comprehensive documentation of all aspects of a modeling project (suggested as a list of elements relevant to any modeling project) and (b) effective communication between modelers, analysts, and decision makers. This approach ensures that there is a clear rationale for using a model for a specific regulatory application.

This guidance recommends best practices to help determine when a model, despite its uncertainties, can be appropriately used to inform a decision. Specifically, it recommends that model developers and users: (a) subject their model to credible, objective peer review; (b) assess the quality of the data they use; (c) corroborate their model by evaluating the degree to which it corresponds to the system being modeled; and (d) perform sensitivity and uncertainty analyses. *Sensitivity analysis* evaluates the effect of changes in input values or assumptions on a model's results. *Uncertainty analysis* investigates the effects of lack of knowledge and other potential sources of error in the model (e.g., the "uncertainty" associated with model parameter values). When conducted in combination, sensitivity and uncertainty analysis allow model users to be more informed about the confidence that can be placed in model results. A model's quality to support a decision becomes better known when information is available to assess these factors.

1. Introduction

1.1 Purpose and Scope of This Document

The U.S. Environmental Protection Agency (EPA) uses a wide range of models to inform decisions that support its mission of protecting human health and safeguarding the natural environment — air, water, and land — upon which life depends. These models include atmospheric and indoor air models, ground water and surface water models, multimedia models, chemical equilibrium models, exposure models, toxicokinetic models, risk assessment models, and economic models. These models range from simple to complex and may employ a combination of scientific, economic, socio-economic, or other types of data.

As stated in the National Research Council (NRC) report *Models in Environmental Regulatory Decision Making*, models are critical to regulatory decision making because the spatial and temporal scales linking environmental controls and environmental quality generally do not allow for an observational approach to understand the relationship between economic activity and environmental quality (NRC 2007). Models have a long history of helping to explain scientific phenomena and predict outcomes and behavior in settings where empirical observations are limited or not available.

This guidance uses the NRC report's definition of a model:

> *A simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system.*

In particular, this guidance focuses on the subset of all models termed "computational models" by the NRC. These are models that use measurable variables, numerical inputs, and mathematical relationships to produce quantitative outputs. (Note that all terms underlined in this document are defined in the Glossary, Appendix A).

As models become increasingly significant in decision making, it is important that the model development and evaluation processes conform to protocols or standards that help ensure the utility, scientific soundness, and defensibility of the models and their outputs for decision making. It is also increasingly important to plan and manage the process of using models to inform decision making (Manno et al. 2008). This guidance document aims to facilitate a widespread understanding of the processes for model development, evaluation, and application and thereby promote their appropriate application to support informed decision making. Recognizing the diversity of modeling applications throughout the Agency, the principles and practices described in the guidance apply generally to all models used to inform Agency decisions, regardless of domain, mode, conceptual basis, form, or rigor level (i.e., varying from screening-level applications to complex analyses) (EPA 2001). The principles presented in this guidance are also applicable to models not used for regulatory purposes as experience has shown that models developed for research and development have often found useful applications in environmental management purposes.

This guidance presents recommendations drawn from Agency white papers on environmental modeling, EPA Science Advisory Board (SAB) reports, NRC's *Models in Environmental Regulatory Decision Making*, and the peer-reviewed literature. It provides an overview of *best practices* for ensuring and evaluating the quality of environmental models.

These practices complement the systematic QA planning process for modeling projects outlined in existing guidance (EPA 2002b). These QA processes produce documentation supporting the quality of the model development and application process (Appendix C, Box C1: Background on EPA Quality System). For example, QA plans should contain performance criteria ("specifications") for a model in the context of its intended use, and these criteria should be developed at the onset of each project. During the model evaluation process, these criteria are subjected to a series of tests of model quality ("checks"). Documentation of these specifications and the evaluation results provides a record of how well a model meets its intended use and the basis for a decision on model acceptability.

The primary purpose of this guidance is to provide specific advice on how to best perform these "checks" during model development, evaluation, and application. Following the best practices emphasized in this document, together with well-documented QA project plans, will help ensure that results of modeling projects and the decisions informed by them heed the principles of the Agency's Information Quality Guidelines (EPA 2002a).

1.2 Intended Audience

This document is intended for a wide range of audiences, including model developers, computer programmers, model users, policy makers who work with models, and affected stakeholders. Model users include those who generate model output (i.e., who set up, parameterize, and run models) and managers who use model outputs.

1.3 Organizational Framework

The main body of this document provides an overview of principles of good modeling for all users. The appendices present technical information and examples that may be more appropriate for specific user groups. For organizational simplicity, the main body of this guidance has separate chapters on the three key topics: model development, model evaluation, and model application. However, it is important to note that these three topics are not strictly sequential, For example, the process of evaluating a model and its input data to ensure their quality should be undertaken and documented during all stages of model development and application.

Chapter 1 serves as a general introduction and outlines the scope of this guidance. **Chapter 2** discusses the role of models in environmental decision making. Figure 1 at the end of Chapter 2 shows the steps in the model development and application process and the role that models play in the public policy process. **Chapters 3 and 4** provide guidance on model development (including problem specification) and model evaluation, respectively. Finally, **Chapter 5** recommends practices for most effectively incorporating information from environmental models into the Agency's policy or regulatory decisions.

Several appendices present more detailed technical information and examples that complement the chapters. **Appendix A** provides definitions for all underlined terms in this guidance, and **Appendix B** summarizes the categories of models that are integral to environmental regulation. **Appendix C** presents additional background information on the QA program and other relevant topics. **Appendix D** presents an overview of best practices that may be used to evaluate models, including more detailed information on the peer review process for models and specific technical guidance on tools for model evaluation.

1.4 Appropriate Implementation of This Document

The principles and practices described in this guidance are designed to apply generally to all types of models; however, EPA program and regional offices may modify the recommendations, as appropriate and necessary to the specific modeling project and application. Each EPA office is responsible for implementing the best practices described in a manner appropriate to meet its needs.

As indicated by the use of non-mandatory language such as “may,” “should,” and “can,” this document provides recommendations and suggestions and does not create legal rights or impose legally binding requirements on EPA or the public.

The Council for Regulatory Environmental Modeling has also developed the Models Knowledge Base — a Web-based inventory of information on models used in EPA — as a companion product to complement this document. This inventory provides convenient access to standardized documentation on the models’ development, scientific basis, user requirements, evaluation studies, and application examples.

2. Modeling for Environmental Decision Support

2.1 Why Are Models Important?

This guidance defines a model as ***"a simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system."*** A model developer sets boundary conditions and determines which aspects of the system are to be modeled, which processes are important, how these processes may be represented mathematically, and what computational methods to use in implementing the mathematics. Thus, models are based on simplifying assumptions and cannot completely replicate the complexity inherent in environmental systems. Despite these limitations, models are essential for a variety of purposes in the environmental field. These purposes tend to fall into two categories:

- To diagnose (i.e., assess what happened) and examine causes and precursor conditions (i.e., why it happened) of events that have taken place.
- To forecast outcomes and future events (i.e., what will happen).

Whether applied to current conditions or envisioned future circumstances, models play an important role in environmental management. They are an important tool to analyze environmental and human health questions and characterize systems that are too complex to be addressed solely through empirical means.

Models can be classified in various ways (see Appendix B) — for example, based on their conceptual basis and mathematical solution, the purpose for which they were developed and are applied, the domain or discipline to which they apply, and the level of resolution and complexity at which they operate. Three categories of regulatory models have been identified based on their purpose or application (CREM 2001):

- **Policy analysis.** The results of policy analysis models affect national policy decisions. These models are used to set policy for large, multi-year programs or concepts — for example national policy on acid rain and phosphorus reduction in the Great Lakes.
- **National regulatory decision making.** These models inform national regulatory decision making after overall policy has been established. Examples include the use of a model to assist in determining federal regulation of a specific pesticide or to aid in establishing national effluent limitations.
- **Implementation applications.** These models are used in situations where policies and regulations have already been made. Their development and use may be driven by court-ordered schedules and the need for local action.

Environmental models are one source of information for Agency decision makers who need to consider many competing objectives. A number of EPA programs make decisions based on information from environmental modeling applications. Within the Agency:

- Models are used to simulate many different processes, including natural (chemical, physical, and biological) systems, economic phenomena, and decision processes.
- Many types of models are employed, including economic, behavioral, physical, engineering design, health, ecological, and fate/transport models.

- The geographic scale of the problems addressed by a model can vary from national scale to an individual site. Examples of different scales include:
  - National air quality models used in decisions about emission requirements.
  - Watershed-scale water quality models used in decisions about permit limits for point sources.
  - Site-scale human health risk models used in decisions about hazardous waste cleanup measures.

Box 1: Examples of EPA Web Sites Containing Model Descriptions for Individual Programs

National Environmental Research Laboratory Models: http://www.epa.gov/nerl/topics/models.html
Atmospheric Sciences Modeling Division: http://www.epa.gov/asmdnerl/index.html
Office of Water's Water Quality Modeling: http://www.epa.gov/waterscience/wqm
Center for Subsurface Modeling Support: http://www.epa.gov/ada/csmos.html
National Center for Computational Toxicology: http://www.epa.gov/ncct
Support Center for Regulatory Atmospheric Modeling: http://www.epa.gov/scram001/aqmindex.htm

Models also have useful applications outside the regulatory context. For example, because models include explicit mathematical statements about system mechanics, they serve as research tools for exploring new scientific issues and screening tools for simplifying and/or refining existing scientific paradigms or software (SAB 1993a, 1989). Models can also help users study the behavior of ecological systems, design field studies, interpret data, and generalize results.

2.2 The Modeling Life-Cycle

The process of developing and applying a model to address a specific decision making need generally follows the iterative progression described in Box 2 and depicted in Figure 1. Models are used to address real or perceived environmental problems. Therefore, a modeling process (i.e., model development, evaluation, and application described in chapters 3, 4, and 5, respectively) is initiated after the Agency has identified an environmental problem and determined that model results could provide useful input for an Agency decision.

Problem identification will be most successful if it involves all parties who would be involved in model development and use (i.e., model developers, intended users, and decision makers). At a minimum, the Agency should develop a relatively simple, plain English problem identification statement.

Box 2: Basic Steps in the Process of Modeling for Environmental Decision Making
(modified from Box 3-1, NRC *Report on Models in Regulatory Environmental Decision Making*)

Step		Modeling Issues
Problem identification and specification: *to determine the right decision-relevant questions and establish modeling objectives*	Definition of model purpose	▪ Goal ▪ Decisions to be supported ▪ Predictions to be made
	Specification of modeling context	▪ Scale (spatial and temporal) ▪ Application domain ▪ User community ▪ Required inputs ▪ Desired output ▪ Evaluation criteria
Model development: *to develop the conceptual model that reflects the underlying science of the processes being modeled, and develop the mathematical representation of that science and encode these mathematical expressions in a computer program*	Conceptual model formulation	▪ Assumptions (dynamic, static, stochastic, deterministic) ▪ State variables represented ▪ Level of process detail necessary ▪ Scientific foundations
	Computational model development	▪ Algorithms ▪ Mathematical/computational methods ▪ Inputs ▪ Hardware platforms and software infrastructure ▪ User interface ▪ Calibration/parameter determination ▪ Documentation
Model evaluation: *to test that the model expressions have been encoded correctly into the computer program and test the model outputs by comparing them with empirical data*	Model testing and revision	▪ Theoretical corroboration ▪ Model components verification ▪ Corroboration (independent data) ▪ Sensitivity analysis ▪ Uncertainty analysis ▪ Robustness determination ▪ Comparison to evaluation criteria set during formulation
Model application: *running the model and analyzing its outputs to inform a decision*	Model use	▪ Analysis of scenarios ▪ Predictions evaluation ▪ Regulations assessment ▪ Policy analysis and evaluation ▪ Model post-auditing

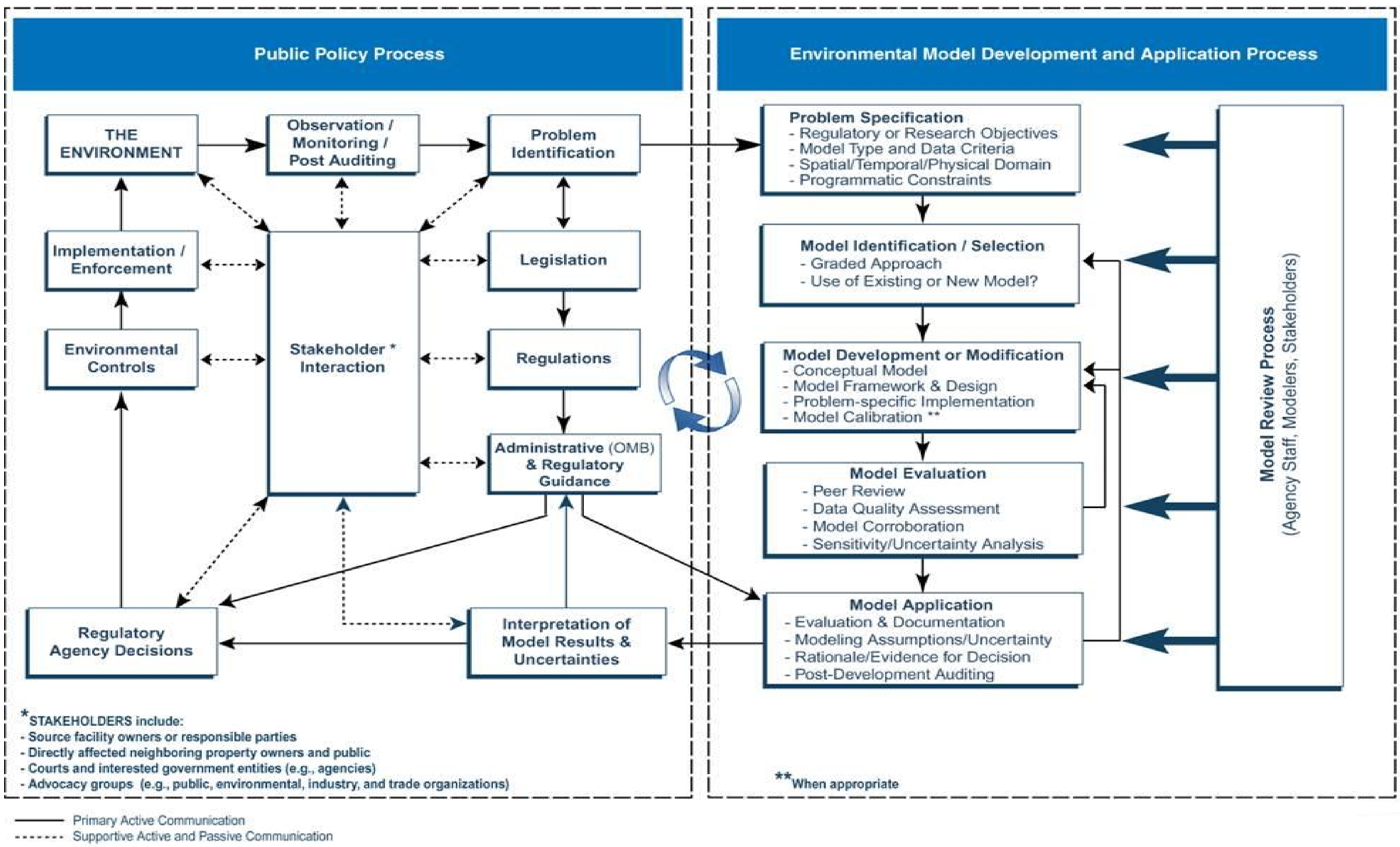


Figure 1. The Role of Modeling in the Public Policy Process.

3. Model Development

Summary of Recommendations for Model Development

- Communication between model developers and model users is crucial during model development.
- Each element of the conceptual model should be clearly described (in words, functional expressions, diagrams, and graphs, as necessary), and the science behind each element should be clearly documented.
- When possible, simple competing conceptual models/hypotheses should be tested.
- Sensitivity analysis should be used early and often.
- The optimal level of model complexity should be determined by making appropriate tradeoffs among competing objectives.
- Where possible, model parameters should be characterized using direct measurements of sample populations.
- All input data should meet data quality acceptance criteria in the QA project plan for modeling.

3.1 Introduction

Model development begins after problem identification — i.e., after the Agency has identified an environmental problem it needs to address and has determined that models may provide useful input for the Agency decision making needed to address the problem (see Section 2.2). In this guidance, model development comprises the steps involved in (1) confirming whether a model is, in fact, a useful tool to address the problem; what type of model would be most useful; and whether an existing model can be used for this purpose; as well as (2) developing an appropriate model if one does not already exist. Model development sets the stage for model evaluation (covered in chapter 3), an ongoing process in which the Agency evaluates the appropriateness of the existing or new model to help address the environmental problem.

Model development can be viewed as a process with three main steps: (a) specify the environmental problem (or set of issues) the model is intended to address and develop the conceptual model, (b) evaluate or develop the model framework (develop the mathematical model), and (c) parameterize the model to develop the application tool. Sections 3.2, 3.3, and 3.4 of this chapter, respectively, describe the various aspects and considerations involved in implementing each of these steps.

As described below, model development is a collaborative effort involving model developers, intended users, and decision makers (the “project team”). The perspective and skills of each group are important to develop a model that will provide an appropriate, credible, and defensible basis for addressing the environmental issue of concern.

A “graded approach” should be used throughout the model development process. This involves repeated examination of the scope, rigor, and complexity of the modeling analysis in light of the intended use of results, degree of confidence needed in the results and Agency resource constraints.

3.2 Problem Specification and Conceptual Model Development

Problem specification, culminating in development of the conceptual model, involves an iterative, collaborative effort among model developers, intended users, and decision makers (the project team) to specify all aspects of the problem that will inform subsequent selection or development of a model framework. Communication between model developers and model users is crucial to clearly establish the objectives of the modeling process; ambiguity at this stage can undermine the chances for success (Manno et al. 2008).

During problem specification, the project team defines the regulatory or research objectives, the type and scope of model best suited to meet those objectives, the data criteria, the model's domain of applicability, and any programmatic constraints. These considerations provide the basis for developing a conceptual model, which depicts or describes the most important behaviors of the system, object, or process relevant to the problem of interest. Problem specification and the resulting conceptual model define the modeling needs sufficiently that the project team can then determine whether an existing model can be used to meet those needs or whether a new model should be developed.

3.2.1 Define the Objectives

The first step in problem specification is to define the regulatory or research objectives (i.e., what questions the model needs to answer). To do so, the team should develop a written statement of modeling objectives that includes the state variables of concern, the stressors driving those state variables, appropriate temporal and spatial scales, and the degree of model accuracy and precision needed.

3.2.2 Determine the Type and Scope of Model Needed

Many different types of models are available, including empirical vs. mechanistic, static vs. dynamic, simulation vs. optimization, deterministic vs. stochastic, and lumped vs. distributed. The project team should discuss and compare alternatives with respect to their ability to meet the objectives in order to determine the most appropriate type of model for addressing the problem.

The scope (i.e., spatial, temporal and process detail) of models that can be used for a particular application can range from very simple to very complex depending on the problem specification and data availability, among other factors. When different types of models may be appropriate for solving different problems, a graded approach should be used to select or develop models that will provide the scope, rigor, and complexity appropriate to the intended use of and confidence needed in the results. Section 3.3.1 provides more information on considerations regarding model complexity.

3.2.3 Determine Data Criteria

This step includes developing data quality objectives (DQOs) and specifying the acceptable range of uncertainty. DQOs (EPA 2000a) provide specifications for model quality and associated checks (see Appendix C, Box C1: Background on EPA Quality System). Well-defined DQOs guide the design of monitoring plans and the model development process (e.g., calibration and verification). The DQOs provide guidance on how to state data needs when limiting decision errors (false positives or false negatives) relative to a given decision.[1] The DQOs should include a statement about the acceptable level of total uncertainty that will still enable model results to be used for the intended purpose (Appendix C, Box C2: Configuration Tests Specified in the QA Program). Uncertainty describes the *lack of knowledge* about models, parameters, constants, data, and beliefs. Defining the ranges of acceptable uncertainty — either qualitatively or quantitatively — helps project planners generate "specifications" for quality assurance planning and partially determines the appropriate boundary conditions and complexity for the model being developed.

3.2.4 Determine the Model's Domain of Applicability

To select an appropriate model, the project team must understand the model's domain of applicability — i.e., the set of conditions under which use of the model is scientifically defensible and the relevant characteristics of the system to be modeled. This involves identifying the environmental domain to be modeled and then specifying the processes and conditions within that domain, including the transport and transformation processes relevant to the policy/management/research objectives, the important time and space scales inherent in transport and transformation processes within that domain in comparison to the time and space scales of the problem objectives, and any peculiar conditions of the domain that will affect model selection or new model construction.

3.2.5 Discuss Programmatic Constraints

At this stage, the project team also needs to consider any factors that could constrain the modeling process. This discussion should include considerations of time and budget, available data or resources to acquire more data, legal and institutional factors, computer resource constraints, and the experience and expertise of the modeling staff.

3.2.6 Develop the Conceptual Model

A conceptual model depicts or describes the most important behaviors of the system, object, or process relevant to the problem of interest. In developing the conceptual model, the model developer may consider literature, fieldwork, applicable anecdotal evidence, and relevant historical modeling projects. The developer should clearly describe (in words, functional expressions, diagrams, and/or graphs) each element of the conceptual model and should document the science behind each element (e.g., laboratory experiments, mechanistic evidence, empirical data supporting the hypothesis, peer-reviewed literature) in mathematical form, when possible. To the extent feasible, the modeler should also provide information on assumptions, scale, feedback mechanisms, and static/dynamic behaviors. When relevant, the strengths and weaknesses of each constituent hypothesis should be described.

---

[1] False rejection decision errors (false positives) occur when the null hypothesis (or baseline condition) is incorrectly rejected based on the sample data. The decision is made assuming the alternate condition or hypothesis to be true when in reality it is false. False acceptance decision errors (false negatives) occur when the null hypothesis (or baseline condition) cannot be rejected based on the available sample data. The decision is made assuming the baseline condition is true when in reality it is false.

3.3 Model Framework Selection or Development

Once the team has specified the problem and type of model needed to address the problem, the next step is to identify or develop a model framework that meets those specifications. A model framework is a formal mathematical specification of the concepts, procedures, and behaviors underlying the system, object, or process relevant to the problem of interest, usually translated into computer software.

For mechanistic modeling of common environmental problems, one or more suitable model frameworks may exist. Many existing model frameworks in the public domain can be used in environmental assessments. Several institutions, including EPA, develop and maintain these model frameworks on an ongoing basis. Ideally, more than one model framework will meet the project needs, and the project team can select the best model for the specified problem. Questions to consider when evaluating existing model frameworks are described below.

Sometimes no model frameworks are appropriate to the task, and EPA will develop a new model framework or modify an existing framework to include the additional capabilities needed to address the project needs.

Some assessments require linking multiple model frameworks, such that the output from one model is used as input data to another model. For example, air quality modeling often links meteorological, emissions, and air chemistry/transport models. When employing linked models, the project team should evaluate each component model, as well as the full system of integrated models, at each stage of the model development and evaluation process.

In all cases, the documentation for the selected model should clearly state why and how the model can and will be used.

As potential model frameworks are identified or developed for addressing the problem, the project team will need to consider several issues, including:

- Does sound science (including peer-reviewed theory and equations) support the underlying hypothesis?
- Is the model's complexity appropriate for the problem at hand?
- Do the quality and quantity of data support the choice of model?
- Does the model structure reflect all the relevant inputs described in the conceptual model?
- Has the model code been developed? If so, has it been verified?

It is recommended that the evaluation process apply the principles of scientific hypothesis testing (Platt 1964) using an iterative approach (Hilborn and Mangel 1997). If the team is evaluating multiple model frameworks, it may be useful to statistically compare the performance of these competing models with observational, field, or laboratory data (Chapter 4).

Box 3: Example of Model Selection Considerations: Arsenic in Drinking Water
(from Box 5-3 of NRC's *Models in Environmental Regulatory Decision Making*)

A major challenge for regulatory model applications is which model to use to inform the decision making process. In this example, several models were available to estimate the cancer incidence associated with different levels of arsenic in drinking water. These models differed according to how age and exposure were incorporated (Morales et al. 2000). All the models assumed that the number of cancers observed in a specific age group of a particular village followed a Poisson model with parameters, depending on the age and village exposure level. Linear, log, polynomial, and spline models for age and exposure were considered.

These various models differed substantially in their fitted values, especially in the critical low-dose area, which is so important for establishing the benchmark dose (BMD) that is used to set a reference dose (RfD). The fitted-dose response model was also strongly affected by whether Taiwanese population data were included as a baseline comparison group. Depending on the particular modeling assumptions used, the estimates of the BMD and associated lower limit (BMDL) varied by over an order of magnitude.

Several strategies are available for choosing among multiple models. One strategy is to pick the "best" model — for example, use one of the popular statistical goodness of fit measures, such as the Akieke (*sic*) information criterion (AIC) or the Bayesian information criterion (BIC). These approaches correspond to picking the model that maximizes log-likelihood, subject to a penalty function reflecting the number of model parameters, thus effectively forcing a trade-off between improving model fit by adding addition model parameters versus having a parsimonious description. In the case of the arsenic risk assessment, however, the noisiness of the data meant that many of the models explored by Morales et al. (2000) were relatively similar in terms of statistical goodness-of-fit criteria. In a follow-up paper, Morales et al. (2006) argued that it was important to address and account for the model uncertainty, because ignoring it would underestimate the true variability of the estimated model fit and, in turn, overestimate confidence in the resulting BMD and lead to "risky decisions" (Volinsky et al. 1997).

Morales et al. suggested using Bayesian model averaging (BMA) as a tool to avoid picking one particular model. BMA combines over a class of suitable models. In practice, estimates based on a BMA approach tend to approximate a weighted average of estimates based on individual models, with the weights reflecting how well each individual model fits the observed data. More precisely, these weights can be interpreted as the probability that a particular model is the true model, given the observed data. Figure 2 shows the results of applying a BMA procedure to the arsenic data:

- Figure 2(a) plots individual fitted models, with the width of each plotted line reflecting the weights.
- Figure 2(b) shows the estimated overall dose-response curve (solid line) fitted via BMA. The shaded area shows the upper and lower limits (2.5% and 97.5% tiles) based on the BMA procedure. The dotted lines show upper and lower limits based on the best fitting models.

Figure 2(b) (L30) effectively illustrates the inadequacy of standard statistical confidence intervals in characterizing uncertainty in settings where there is substantial model uncertainty. The BMA limits coincide closely with the individual curves at the upper level of the dose-response curve where all the individual models tend to give similar results.

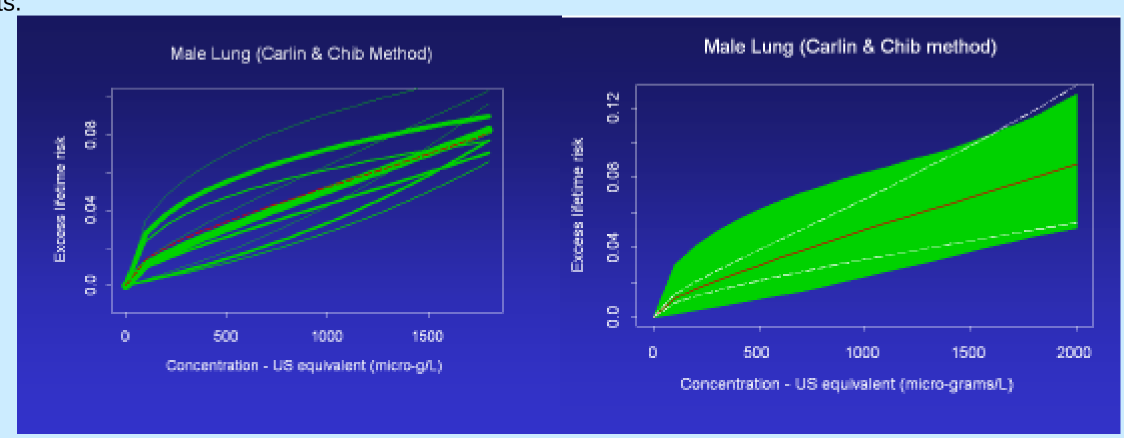


Figure 2. (a) Individual dose-response models, and (b) overall dose-response model fitted using the Bayesian model averaging approach. Source: Morales et al. 2000.

3.3.1 Model Complexity

During the problem specification stage, the project team will have considered the degree of complexity desired for the model (see Section 3.2.2). As described below, model complexity influences uncertainty. Models tend to uncertainty as they become increasingly simple or increasingly complex. Thus complexity is an important parameter to consider when choosing among competing model frameworks or determining the suitability of the existing model framework to the problem of concern. For the reasons described below, the optimal choice generally is a model that is no more complicated than necessary to inform the regulatory decision. For the same reasons, model complexity is an essential parameter to consider when developing a new model framework.

Uncertainty exists when knowledge about specific factors, parameters (inputs), or models is incomplete. Models have two fundamental types of uncertainty:

- Model framework uncertainty, which is a function of the soundness of the model's underlying scientific foundations.
- Data uncertainty, which arises from measurement errors, analytical imprecision, and limited sample size during collection and treatment of the data used to characterize the model parameters.

These two types of uncertainty have a reciprocal relationship, with one increasing as the other decreases. Thus, as illustrated in Figure 3, an optimal level of complexity (the "point of minimum uncertainty") exists for every model.

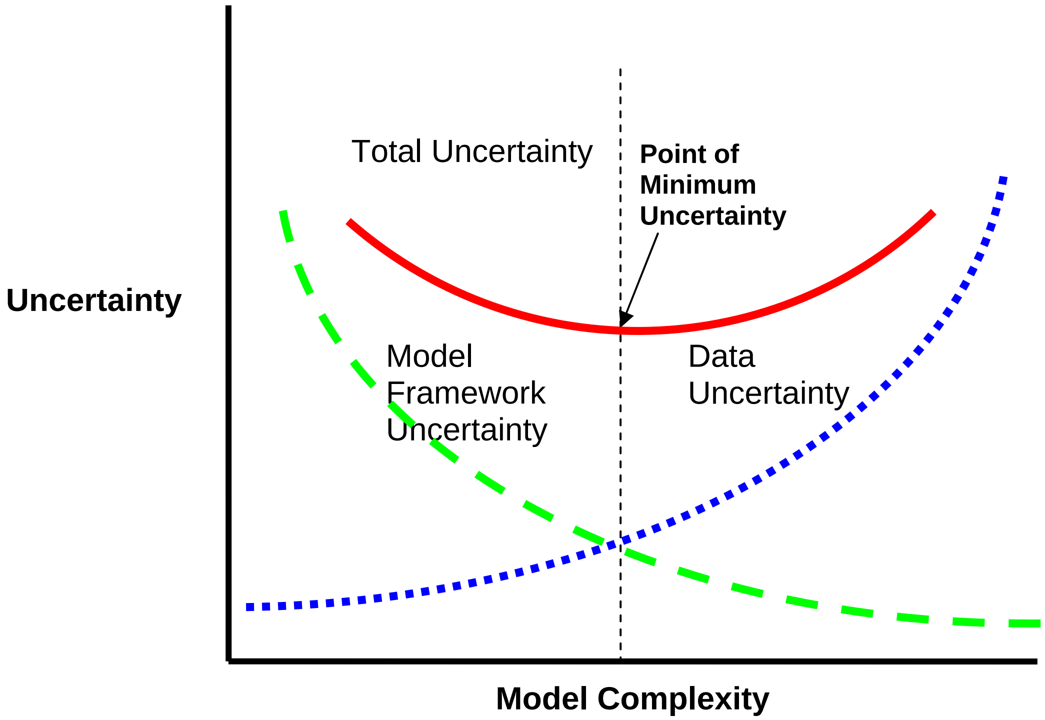


Figure 3. Relationship between model framework uncertainty and data uncertainty, and their combined effect on total model uncertainty.
(Adapted from Hanna 1988).

For example, air quality modelers must sometimes compromise when choosing among the physical processes that will be treated explicitly in the model. If the objective is to estimate the pattern of pollutant concentration values near one (or several) source(s), then chemistry is typically of little importance because the distances between the pollutant source and receptor are generally too short for chemical formation and destruction to greatly affect pollutant concentrations. However, in such situations, other factors tend to have a significant effect and must be properly accounted for in the model. These may include building wakes, initial characterization of source release conditions and size, rates of diffusion of pollutants released as they are transported downwind, and land use effects on plume transport. Conversely, when the objective is to estimate pollutant concentrations further from the source, chemistry becomes more important because there is more time for chemical reactions to take place, and initial source release effects become less important because the pollutants become well-mixed as they travel through the atmosphere. To date, attempts to model both near-field dispersion effects and chemistry have been inefficient and slow on desktop computers.

Because of these competing objectives, parsimony (economy or simplicity of assumptions) is desirable in a model. As Figure 3 illustrates, as models become more complex to treat more physical processes, their performance tends to degrade because they require more input variables, leading to greater data uncertainty. Because different models contain different types and ranges of uncertainty, it can useful to conduct sensitivity analysis early in the model development phase to identify the relative importance of model parameters. Sensitivity analysis is the process of determining how changes in the model input values or assumptions (including boundaries and model functional form) affect the model outputs (Morgan and Henrion 1990).

Model complexity can be constrained by eliminating parameters when sensitivity analyses (Chapter 4/Appendix D) show that they do not significantly affect the outputs and when there is no process-based rationale for including them. However, a variable of little significance in one application of a model may be more important in a different application. In past reviews of Agency models, the SAB has supported the general guiding principle of simplifying complex models, where possible, for the sake of transparency (SAB 1988), but has emphasized that care should be taken not to eliminate important parameters from process-based models simply because data are unavailable or difficult to obtain (SAB 1989). In any case, the quality and resolution of available data will ultimately constrain the type of model that can be applied. Hence, it is important to identify the existing data and and/or field collection efforts that are needed to adequately parameterize the model framework and support the application of a model. The NRC Committee on Models in the Regulatory Decision Process recommended that models used in the regulatory process should be no more complicated than is necessary to inform regulatory decision and that it is often preferable to omit capabilities that do not substantially improve model performance (NRC 2007).

3.3.2 Model Coding and Verification

Model coding translates the mathematical equations that constitute the model framework into functioning computer code. Code verification ascertains that the computer code has no inherent numerical problems with obtaining a solution. Code verification tests whether the code performs according to its design specifications. It should include an examination of the numerical technique in the computer code for consistency with the conceptual model and governing equations (Beck et al. 1994). Independent testing of the code once it is fully developed can be useful as an additional check of integrity and quality.

Several early steps can help minimize later programming errors and facilitate the code verification process. For example:

- **Using "comment" lines to describe the purpose of each component within the code** during development makes future revisions and improvements by different modelers and programmers more efficient.
- **Using a flow chart when the conceptual model is developed** and before coding begins helps show the overall structure of the model program. This provides a simplified description of the calculations that will be performed in each step of the model.

Breaking the program/model into component parts or modules is also useful for careful consideration of model behavior in an encapsulated way. This allows the modeler to test the behavior of each sub-component separately, expediting testing and increasing confidence in the program. A module is an independent piece of software that forms part of one or more larger programs. **Breaking large models into discrete modules** facilitates testing and debugging (locating/correcting errors) compared to large programs. The approach also makes it easier to re-use relevant modules in future modeling projects, or to update, add, or remove sections of the model without altering the overall program structure.

Use of generic algorithms for common tasks can often save time and resources, allowing efforts to focus on developing and improving the original aspects of a new model. An algorithm is a precise rule (or set of rules) for solving some problem. Commonly used algorithms are often published as "recipes" with publicly available code (e.g., Press 1992). Developers should review existing Agency models and code to minimize duplication of effort. The CREM models knowledge base, which will contain a Web-accessible inventory of models, will provide a resource model developers can use for this purpose.

Software engineering has evolved rapidly in recent years and continues to advance rapidly with changes in technology and user platforms. For example, some of the general recommendations for developing computer code given above do not apply to models that are developed using object-oriented platforms. Object-oriented platform model systems use a collection of cooperating "objects." These objects are treated as instances of a class within a class hierarchy, where a class is a set of objects that share a common structure and behavior. The structure of a class is determined by the class variables, which represent the state of an object of that class; the behavior is given by the set of methods associated with the class (Booch 1994). When models are developed with object-oriented platforms, the user should print out the actual mathematical relationships the platform generates and review them as part of the code validation process.

Many references on programming style and conventions provide specific, technical suggestions for developing and testing computer code (e.g., *The Elements of Programming Style* [Kernigham and Plaugher 1988]). In addition, the *Guidance for Quality Assurance Project Plans for Modeling* (EPA 2002b) suggests a number of practices during code verification to "check" how well it follows the "specifications" laid out during QA planning (Appendix C, Box C2: Configuration Tests Specified in the QA Program).

3.4 Application Tool Development

Once a model framework has been selected or developed, the modeler populates the framework with the specific system characteristics needed to address the problem, including geographic boundaries of the model domain, boundary conditions, pollution source inputs, and model parameters. In this manner, the generic computational capabilities of the model framework are converted into an application tool to assess a specific problem occurring at a specific location. Model parameters are terms in the model that are fixed during a model run or simulation but can be changed in different runs, either to conduct sensitivity analysis or to perform an uncertainty analysis when probabilistic distributions are selected to model parameters or achieve calibration (defined below) goals. Parameters can be quantities estimated from sample data that characterize statistical populations or they can be constants such as the speed of light and gravitational force. Other activities at this stage of model development include creating a user guide for the model, assembling datasets for model input parameters, and determining hardware requirements.

3.4.1 Input Data

As mentioned above, the accuracy, variability, and precision of input data used in the model is a major source of uncertainty:

- Accuracy refers to the closeness of a measured or computed value to its "true" value (the value obtained with perfect information). Due to the natural heterogeneity and random variability (stochasticity) of many environmental systems, this "true" value exists as a distribution rather than a discrete value.
- Variability refers to differences attributable to true heterogeneity or diversity in model parameters. Because of variability, the "true" value of model parameters is often a function of the degree of spatial and temporal aggregation.
- Precision refers to the quality of being reproducible in outcome or performance. With models and other forms of quantitative information, precision often refers to the number of decimal places to which a number is computed. This is a measure of the "preciseness" or "exactness" of the model.

Modelers should always select the most appropriate data — as defined by QA protocols for field sampling, data collection, and analysis (EPA 2002c, 2002d, 2000b) — for use in modeling analyses. Whenever possible, all parameters should be directly measured in the system of interest.

Box 4: Comprehensive Everglades Restoration Plan: An Example of the Interdependence of Models and

(from NRC's *Models in Environmental Regulatory Decision Making*)

The restoration of the Florida Everglades is the largest ecosystem restoration ever planned in terms of geographical extent and number of individual components. The NRC Committee on Restoration of the Greater Everglades Ecosystem, which was charged with providing scientific advice on this effort, describes the role that modeling and measurements should play in implementing an adaptive approach to restoration (NRC 2003). Under the committee's vision, monitoring of hydrological and ecological performance measures should be integrated with mechanistic modeling and experimentation to better understand how the Everglades function and how the system will respond to management practices and external stresses. Because individual components of the restoration plan will be staggered in time, the early components can provide scientific feedback to guide and refine implementation of later components of the plan.

The NRC Committee on Models in the Regulatory Decision Process recommends that: "…using adapting strategies to coordinate data collection and modeling should be a priority for decision makers and those responsible for regulatory model development and application. The interdependence of measurements and modeling needs to be fully considered as early as the conceptual model development phase."

3.4.2 Model Calibration

Some models are "calibrated" to set parameters. Appendix C provides guidance on model calibration as a QA project plan element (see Box C3: Quality Assurance Planning Suggestions for Model Calibration Activities). In this guidance, calibration is defined as the process of adjusting model parameters within physically defensible ranges until the resulting predictions give the best possible fit to the observed data (EPA 1994b). In some disciplines, calibration is also referred to as parameter estimation (Beck et al. 1994).

Most process-oriented environmental models are under-determined; that is, they contain more uncertain parameters than state variables that can be used to perform a calibration. Sensitivity analysis can be used to identify key processes influencing the state variables. Sometimes the rate constant for a key process can be measured directly — for example, measuring the rate of photosynthesis (a process) in a lake in addition to the phytoplankton biomass (a state variable). Direct measurement of rate parameters can reduce model uncertainty.

When a calibration database has been developed and improved over time, the initial adjustments and estimates may need period recalibration. When data for quantifying one or more parameter values are limited, calibration exercises can be used to find solutions that result in the "best fit" of the model. However, these solutions will not provide meaningful information unless they are based on *measured* physically defensible ranges. Therefore, this type of calibration should be undertaken with caution.

Because of these concerns, the use of calibration to improve model performance varies among EPA offices and regions. For a particular model, the appropriateness of calibration may be a function of the modeling activities undertaken. For example, the Office of Water's standard practice is to calibrate well-established model frameworks such as CE-QUAL-W2 (a model for predicting temperature fluctuations in rivers) to a specific system (e.g., the Snake River). This calibration generates a site-specific tool (e.g., the "Snake River Temperature" model). In contrast, the Office of Air and Radiation (OAR) more commonly uses model frameworks and models that do not need site-specific adjustments. For example, certain types of air models (e.g., gaussian plume) are parameterized for a range of meteorological conditions, and thus do not need to be "recalibrated" for different geographic locations (assuming the range of conditions is appropriate for the model). OAR also seeks to avoid artificial improvements in model performance by adjusting model inputs outside the ranges supported by the empirical databases. These practices prompted OAR to issue the following statement on model calibration in their *Guideline on Air Quality Models* (EPA 2003b):

> *Calibration of models is not common practice and is subject to much error and misunderstanding. There have been attempts by some to compare model estimates and measurements on an event-by-event basis and then calibrate a model with results of that comparison. This approach is severely limited by uncertainties in both source and meteorological data and therefore it is difficult to precisely estimate the concentration at*

an exact location for a specific increment of time. Such uncertainties make calibration of models of questionable benefit. Therefore, model calibration is unacceptable.

In general, however, models benefit from thoughtful adaptation that will enable them to respond adequately to the specifics of each regulatory problem to which they are applied.

4. Model Evaluation

Summary of Recommendations for Model Evaluation

appropriately used to inform a decision.

- Model evaluation addresses the soundness of the science underlying a model, the quality and quantity of available data, the degree of correspondence with observed conditions, and the appropriateness of a model for a given application.
- Recommended components of the evaluation process include: (a) credible, objective peer review; (b) QA project planning and data quality assessment; (c) qualitative and/or quantitative model corroboration; and (d) sensitivity and uncertainty analyses.
- Quality is an attribute of models that is meaningful only within the context of a specific model application. Determining whether a model serves its intended purpose involves in-depth discussions between model developers and the users responsible for applying for the model to a particular problem.
- Information gathered during model evaluation allows the decision maker to be better positioned to formulate decisions and policies that take into account all relevant issues and concerns.

4.1 Introduction

> *Models will always be constrained by computational limitations, assumptions and knowledge gaps. They can best be viewed as tools to help inform decisions rather than as machines to generate truth or make decisions. Scientific advances will never make it possible to build a perfect model that accounts for every aspect of reality or to prove that a given model is correct in all aspects for a particular regulatory application. These characteristics…suggest that model evaluation be viewed as an integral and ongoing part of the life cycle of a model, from problem formulation and model conceptualization to the development and application of a computational tool.*
>
> — *NRC Committee on Models in the Regulatory Decision Process (NRC 2007)*

The natural complexity of environmental systems makes it difficult to mathematically describe all relevant processes, including all the intrinsic mechanisms that govern their behavior. Thus, policy makers often rely on models as tools to approximate reality when making decisions that affect environmental systems. The challenge facing model developers and users is determining when a model, despite its uncertainties, can be appropriately used to inform a decision. Model evaluation is the process used to make this determination. In this guidance, model evaluation is defined as *the process used to generate information to determine whether a model and its analytical results are of a quality sufficient to serve as the basis for a decision.* Model evaluation is conducted over the life cycle of the project, from development through application.

Box 5: Model Evaluation Versus Validation Versus Verification

Model evaluation should not be confused with model validation. Different disciplines assign different meanings to these terms and they are often confused. For example, Suter (1993) found that among models used for risk assessments, misconception often arises in the form of the question "Is the model valid?" and statements such as "No model should be used unless it has been validated." Suter further points out that "validated" in this context means (a) proven to correspond exactly to reality or (b) demonstrated through experimental tests to make consistently accurate predictions.

Because every model contains simplifications, predictions derived from a model can never be completely accurate and a model can never correspond exactly to reality. In addition, "validated models" (e.g., those that have been shown to correspond to field data) do not necessarily generate accurate predictions of reality for multiple applications (Beck 2002a). Thus, some researchers assert that no model is ever truly "validated"; models can only be invalidated for a specific application (Oreskes et al. 1994). Accordingly, this guidance focuses on process and techniques for *model evaluation* rather than model validation or invalidation.

"Verification" is another term commonly applied to the evaluation process. However, in this guidance and elsewhere, model verification typically refers to model code verification as defined in the model development section. For example, the NRC Committee on Models in the Regulatory Decision Process (NRC 2007) provides the following definition:

> *Verification* refers to activities that are designed to confirm that the mathematical framework embodied in the module is correct and that the computer code for a module is operating according to its intended design so that the results obtained compare favorably with those obtained using known analytical solutions or numerical solutions from simulators based on similar or identical mathematical frameworks.

In simple terms, model evaluation provides information to help answer four main questions (Beck 2002b):

1. How have the principles of sound science been addressed during model development?
2. How is the choice of model supported by the quantity and quality of available data?
3. How closely does the model approximate the real system of interest?
4. How does the model perform the specified task while meeting the objectives set by QA project planning?

These four factors address two aspects of model quality. The first factor focuses on the intrinsic mechanisms and generic properties of a model, *regardless of the particular task to which it is applied*. In contrast, the latter three factors are evaluated in the context of the use of a model *within a specific set of conditions*. Hence, it follows that model quality is an attribute that is meaningful only within the context of a *specific model application*. A model's quality to support a decision becomes known when information is available to assess these factors.

The NRC committee recommends that evaluation of a regulatory model continue throughout the life of a model and that an evaluation plan could:

- Describe the model and its intended uses.
- Describe the relationship of the model to data, including the data for both inputs and corroboration.

- Describe how such data and other sources of information will be used to assess the ability of the model to meet its intended task.
- Describe all the elements of the evaluation plan by using an outline or diagram that shows how the elements relate to the model's life cycle.
- Describe the factors or events that might trigger the need for major model revisions or the circumstances that might prompt users to seek an alternative model. These can be fairly broad and qualitative.
- Identify the responsibilities, accountabilities, and resources needed to ensure implementation of the evaluation plan.

As stated above, the goal of model evaluation is to ensure model quality. At EPA, quality is defined by the Information Quality Guidelines (IQGs) (EPA 2002a). The IQGs apply to all information that EPA disseminates, including models, information from models, and input data (see Appendix C, Box C4: Definition of Quality). According to the IQGs, quality has three major components: integrity, utility, and objectivity. This chapter focuses on addressing the four questions listed above by evaluating the third component, objectivity — specifically, how to ensure the objectivity of information from models by considering their accuracy, bias, and reliability.

- Accuracy, as described in Section 2.4, is the closeness of a measured or computed value to its "true" value, where the "true" value is obtained with perfect information.
- Bias describes any systematic deviation between a measured (i.e., observed) or computed value and its "true" value. Bias is affected by faulty instrument calibration and other measurement errors, systematic errors during data collection, and sampling errors such as incomplete spatial randomization during the design of sampling programs.
- Reliability is the confidence that (potential) users have in a model and its outputs such that they are willing to use the model and accept its results (Sargent 2000). Specifically, reliability is a function of the model's performance record and its conformance to best available, practicable science.

This chapter describes principles, tools, and considerations for model evaluation throughout all stages of development and application. Section 4.2 presents a variety of qualitative and quantitative best practices for evaluating models. Section 4.3 discusses special considerations for evaluating proprietary models. Section 4.4 explains why retrospective analysis of models, conducted after a model has been applied, can be important to improve individual models and regulatory policies and to systematically enhance the overall modeling field. Finally, Section 4.5 describes how the evaluation process culminates in a decision whether to apply the model to decision making. Section 4.6 reviews the key recommendations from this chapter.

4.2 Best Practices for Model Evaluation

The four questions listed above address the soundness of the science underlying a model, the quality and quantity of available data, the degree of correspondence with observed conditions, and the appropriateness of a model for a given application. This guidance describes several "tools" or best practices to address these questions: peer review of models; QA project planning, including data quality assessment; model corroboration (qualitative and/or quantitative evaluation of a model's accuracy and predictive capabilities); and sensitivity and uncertainty analysis. These tools and practices include both qualitative and quantitative techniques:

- Qualitative assessments: Some of the uncertainty in model predictions may arise from sources whose uncertainty cannot be quantified. Examples are uncertainties about the theory underlying the model, the manner in which that theory is mathematically expressed to represent the environmental components, and the theory being modeled. Subjective evaluation of experts may be needed to determine appropriate values for model parameters and inputs that cannot be directly observed or measured (e.g., air emissions estimates). Qualitative assessments are needed for these sources of uncertainty. These assessments may involve expert elicitation regarding the system's behavior and comparison with model forecasts.
- Quantitative assessments: The uncertainty in some sources — such as some model parameters and some input data — can be estimated through quantitative assessments involving statistical uncertainty and sensitivity analyses. These types of analyses can also be used to quantitatively describe how model estimates of current conditions may be expected to differ from comparable field observations. However, since model predictions are not directly observed, special care is needed when quantitatively comparing model predictions with field data.

As discussed previously, model evaluation is an iterative process. Hence, these tools and techniques may be effectively applied throughout model development, testing, and application and should not be interpreted as sequential steps for model evaluation.

Model evaluation should always be conducted using a graded approach that is adequate and appropriate to the decision at hand (EPA 2001, 2002b). This approach recognizes that model evaluation can be modified to the circumstances of the problem at hand and that programmatic requirements are varied. For example, a screening model (a type of model designed to provide a "conservative" or risk-averse answer) that is used for risk management should undergo rigorous evaluation to avoid false negatives, while still not imposing unreasonable data-generation burdens (false positives) on the regulated community. Ideally, decision makers and modeling staff work together at the onset of new projects to identify the appropriate degree of model evaluation (see Section 3.1).

External circumstances can affect the rigor required in model evaluation. For example, when the likely result of modeling will be costly control strategies and associated controversy, more detailed model evaluation may be necessary. In these cases, many aspects of the modeling may come under close scrutiny, and the modeler must document the findings of the model evaluation process and be prepared to answer questions that will arise about the model. A deeper level of model evaluation may also be appropriate when modeling unique or extreme situations that have not been previously encountered.

Finally, as noted earlier, some assessments require the use of multiple, linked models. This linkage has implications for assessing uncertainty and applying the system of models. Each component model as well as the full system of integrated models must be evaluated.

Sections 4.2.1 and 4.2.2, on peer review of models and quality assurance protocols for input data, respectively, are drawn from existing guidance. Section 4.2.3, on model corroboration activities and the use of sensitivity and uncertainty analysis, provides new guidance for model evaluation (along with Appendix D).

Box 6: Examples of Life Cycle Model Evaluation

The value in evaluating a model from the conceptual stage through the use stage is illustrated in a multi-year project conducted by the Organization for Economic Cooperation and Development (OECD). The project sought to develop a screening model that could be used to assess the persistence and long-range transport potential of chemicals. To ensure its effectiveness, the screening model needed to be a consensus model that had been evaluated against a broad set of available models and data.

This project began at a 2001 workshop to set model performance and evaluation goals that would provide the foundation for subsequent model selection and development (OECD 2002). OECD then established an expert group in 2002. This group began its work by developing and publishing a guidance document on using multimedia models to estimate environmental persistence and long-range transport. From 2003 to 2004, the group compared and assessed the performance of nine available multimedia fate and transport models (Fenner et al. 2005; Klasmeier et al. 2006). The group then developed a parsimonious consensus model representing the minimum set of key components identified in the model comparison. They convened three international workshops to disseminate this consensus model and provide an ongoing model evaluation forum (Scheringer et al. 2006).

In this example, more than half the total effort was invested in the conceptual and model formulation stages, and much of the effort focused on performance evaluation. The group recognized that each model's life cycle is different, but noted that attention should be given to developing consensus-based approaches in the model concept and formulation stages. Conducting concurrent evaluations at these stages in this setting resulted in a high degree of buy-in from the various modeling groups.

4.2.1 Scientific Peer Review

Peer review provides the main mechanism for independent evaluation and review of environmental models used by the Agency. Peer review provides an independent, expert review of the evaluation in Section 4.1; therefore, its purpose is two-fold:

- To evaluate whether the assumptions, methods, and conclusions derived from environmental models are based on sound scientific principles.
- To check the scientific appropriateness of a model for informing a specific regulatory decision. (The latter objective is particularly important for secondary applications of existing models.)

Information from peer reviews is also helpful for choosing among multiple competing models for a specific regulatory application. Finally, peer review is useful to identify the limitations of existing models. Peer review is *not* a mechanism to comment on the *regulatory decisions* or policies that are informed by models (EPA 2000c).

Peer review charge questions and corresponding records for peer reviewers to answer those questions should be incorporated into the quality assurance project plan, developed during assessment planning (see Section 4.2.2, below). For example, peer reviews may focus on whether a model meets the objectives or specifications that were set as part of the quality assurance plan (see EPA 2002b) (see Section 3.1).

All models that inform *significant*[2] regulatory decisions are candidates for peer review (EPA 2000c, 1993) for several reasons:

- Model results will be used as a basis for major regulatory or policy/guidance decision making.
- These decisions likely involve significant investment of Agency resources.
- These decisions may have inter-Agency or cross-agency implications/applicability.

Existing guidance recommends that a new model should be scientifically peer-reviewed prior to its first application; for subsequent applications, the program manager should consider the scientific/technical complexity and/or the novelty of the particular circumstances to determine whether additional peer review is needed (EPA 1993). To conserve resources, peer review of "similar" applications should be avoided.

Models used for secondary applications (existing EPA models or proprietary models) will generally undergo a different type of evaluation than those developed with a specific regulatory information need in mind. Specifically, these reviews may deal more with uncertainty about the appropriate application of a model to a specific set of conditions than with the science underlying the model framework. For example, a project team decides to assess a water quality problem using WASP, a well-established water quality model framework. The project team determines that peer review of the model framework itself is not necessary, and the team instead conducts a peer review on their specific application of the WASP framework.

The following aspects of a model should be peer-reviewed to establish scientific credibility (SAB 1993a, EPA 1993):

- Appropriateness of input data.
- Appropriateness of boundary condition specifications.
- Documentation of inputs and assumptions.
- Applicability and appropriateness of selected parameter values.
- Documentation and justification for adjusting model inputs to improve model performance (calibration).
- Model application with respect to the range of its validity.
- Supporting empirical data that strengthen or contradict the conclusions that are based on model results.

To be most effective and maximize its value, external peer review should begin as early in the model *development* phase as possible (EPA 2000b). Because peer review involves significant time and resources, these allocations must be incorporated into components of the project planning and any

[2] Executive Order 12866 (58 FR 51735) requires federal agencies to determine whether a regulatory action is "significant" and therefore, subject to the requirements of the Executive Order, including review by the Office of Management and Budget. The Order defines "significant regulatory action" as one "that is likely to result in a rule that may: (1) Have an annual effect on the economy of $100 million or more or adversely affect in a material way the economy, a sector of the economy, productivity, competition, jobs, the environment, public health or safety, or State, local, or tribal governments or communities; (2) Create a serious inconsistency or otherwise interfere with an action taken or planned by another agency; (3) Materially alter the budgetary impacts of entitlements, grants, user fees, or loan programs or the rights and obligations of recipients thereof; or (4) Raise novel legal or policy issues arising out of legal mandates, the President's priorities, or the principles set forth in [the] Order." Section 2(f).

related contracts. Peer review in the early stages of model development can help evaluate the conceptual basis of models and potentially save time by redirecting misguided initiatives, identifying alternative approaches, or providing strong technical support for a potentially controversial position (SAB 1993a, EPA 1993). Peer review in the later stages of model development is useful as an independent external review of model code (i.e., model verification). External peer review of the *applicability* of a model to a particular set of conditions should be considered well in advance of any decision making, as it helps avoid inappropriate applications of a model for specific regulatory purposes (EPA 1993).

The peer review logistics are left to the discretion of the managers responsible for applying the model results to decision making. Mechanisms for accomplishing external peer review include (but are not limited to):

- Using an ad hoc panel of scientists.[3]
- Using an established external peer review mechanism such as the SAB
- Holding a technical workshop.[4]

Several sources provide guidance for determining the qualifications and number of reviewers needed for a given modeling project (SAB 1993a; EPA 2000c, 1993, 1994a). Key aspects are summarized in Appendix D of this guidance.

4.2.2 Quality Assurance Project Planning and Data Quality Assessment

Like peer review, data quality assessment addresses whether a model has been developed according to the principles of sound science. While some variability in data is unavoidable (see Section 4.2.3.1), adhering to the tenets of data quality assessment described in other Agency guidance[5] (Appendix D, Box D2: Quality Assurance Planning and Data Acceptance Criteria) helps minimize data uncertainty.

Well-executed QA project planning also helps ensure that a model performs the specified task, which addresses the fourth model evaluation question posed in Section 4.1. As discussed above, evaluating the degree to which a modeling project has met QA objectives is often a function of the external peer review process. The *Guidance for Quality Assurance Project Plans for Modeling* (EPA 2002b) provides general information about how to document quality assurance planning for modeling (e.g., specifications

---

[3] The formation and use of an ad hoc panel of peer reviewers may be subject to the Federal Advisory Committee Act (FACA). Compliance with FACA's requirements is summarized in Chapter Two of the *Peer Review Handbook,* "Planning a Peer Review" (EPA 2000c). Guidance on compliance with FACA may be sought from the Office of Cooperative Environmental Management. Legal questions regarding FACA may be addressed to the Cross-Cutting Issues Law Office in the Office of General Counsel.

[4] Note that a technical workshop held for peer review purposes is not subject to FACA *if the reviewers provide individual opinions.* [Note that there is no "one time meeting" exemption from FACA. The courts have held that even a single meeting can be subject to FACA.] An attempt to obtain group advice, whether it be consensus or majority-minority views, likely would trigger FACA requirements.

[5] Other guidance that can help ensure the quality of data used in modeling projects includes:

- *Guidance for the Data Quality Objectives Process*, a systematic planning process for environmental data collection (EPA 2000a).
- *Guidance on Choosing a Sampling Design for Environmental Data Collection*, on applying statistical sampling designs to environmental applications (EPA 2002c).
- *Guidance for Data Quality Assessment: Practical Methods for Data Analysis*, to evaluate the extent to which data can be used for a specific purpose (EPA 2000b).

or assessment criteria development, assessments of various stages of the modeling process; reports to management as feedback for corrective action; and finally the process for acceptance, rejection, or qualification of the output for use) to conform with EPA policy and acquisition regulations. Data quality assessments are a key component of the QA plan for models.

Both the quality and quantity (representativeness) of supporting data used to parameterize and (when available) corroborate models should be assessed during all relevant stages of a modeling project. Such assessments are needed to evaluate whether the available data are sufficient to support the choice of the model to be applied (question 2, Section 4.1), and to ensure that the data are sufficiently representative of the true system being modeled to provide meaningful comparison to observational data (question 3, Section 4.1).

4.2.3 Corroboration, Sensitivity Analysis, and Uncertainty Analysis

The question "How closely does the model approximate the real system of interest?" is unlikely to have a simple answer. In general, answering this question is not simply a matter of comparing model results and empirical data. As noted in Section 3.1, when developing and using an environmental model, modelers and decision makers should consider what degree of uncertainty is acceptable within the context of a specific model application. To do this, they will need to understand the uncertainties underlying the model. This section discusses three approaches to gaining this understanding:

- Model corroboration (Section 4.2.3.2), which includes all quantitative and qualitative methods for evaluating the degree to which a model corresponds to reality.
- Sensitivity analysis (Section 4.2.3.3), which involves studying how changes in a model's input values or assumptions affect its output or response.
- Uncertainty analysis (Section 4.2.3.3), which investigates how a model might be affected by the lack of knowledge about a certain population or the real value of model parameters.

Where practical, the recommended analyses should be conducted and their results reported in the documentation supporting the model. Section 4.2.3.1 describes and defines the various types of uncertainty, and associated concepts, inherent in the modeling process that model corroboration and sensitivity and uncertainty analysis can help assess.

4.2.3.1 Types of Uncertainty

Uncertainties are inherent in all aspects of the modeling process. Identifying those uncertainties that *significantly* influence model outcomes (either qualitatively or quantitatively) and communicating their importance is key to successfully integrating information from models into the decision making process. As defined in Chapter 3, uncertainty is the term used in this guidance to describe incomplete knowledge about specific factors, parameters (inputs), or models. For organizational simplicity, uncertainties that affect model quality are categorized in this guidance as:

- **Model framework uncertainty,** resulting from incomplete knowledge about factors that control the behavior of the system being modeled; limitations in spatial or temporal resolution; and simplifications of the system.

- **Model input uncertainty,** resulting from data measurement errors, inconsistencies between measured values and those used by the model (e.g., in their level of aggregation/averaging), and parameter value uncertainty.
- **Model niche uncertainty,** resulting from the use of a model outside the system for which it was originally developed and/or developing a larger model from several existing models with different spatial or temporal scales.

Box 7: Example of Model Input Uncertainty

The NRC's *Models in Environmental Regulatory Decision Making* provides a detailed example, summarized below, of the effect of model input uncertainty on policy decisions.

The formation of ozone in the lower atmosphere (troposphere) is an exceedingly complex chemical process that involves the interaction of oxides of nitrogen (NO_x), volatile organic compounds (VOCs), sunlight, and dynamic atmospheric processes. The basic chemistry of ozone formation was known in the early 1960s (Leighton 1961). Reduction of ozone concentrations generally requires controlling either or both NO_x and VOC emissions. Due to the nonlinearity of atmospheric chemistry, selection of the emission-control strategy traditionally relied on air quality models.

One of the first attempts to include the complexity of atmospheric ozone chemistry in the decision making process was a simple observation-based model, the so-called Appendix J curve (36 Fed. Reg. 8166 [1971]). The curve was used to indicate the percentage VOC emission reduction required to attain the ozone standard in an urban area based on peak concentration of photochemical oxidants observed in that area. Reliable NO_x data were virtually nonexistent at the time; Appendix J was based on data from measurements of ozone and VOC concentrations from six U.S. cities. The Appendix J curve was based on the hypothesis that reducing VOC emissions was the most effective emission-control path, and this conceptual model helped define legislative mandates enacted by Congress that emphasized controlling these emissions.

The choice in the 1970s to concentrate on VOC controls was supported by early results from models. Though new results in the 1980s showed higher-than-expected biogenic VOC emissions, EPA continued to emphasize VOC controls, in part because the schedule that Congress and EPA set for attaining the ozone ambient air quality standards was not conducive to reflecting on the basic elements of the science (Dennis 2002).

VOC reductions from the early 1970s to the early 1990s had little effect on ozone concentrations. Regional ozone models developed in the 1980s and 1990s suggested that controlling NO_x emissions was necessary in addition to, or instead of, controlling VOCs to reduce ozone concentrations (NRC 1991). The shift in the 1990s toward regulatory activities focusing on NO_x controls was partly due to the realization that historical estimates of emissions and the effectiveness of various control strategies in reducing emissions were not accurate. In other words, ozone concentrations had not been reduced as much as hoped over the past three decades, in part because emissions of some pollutants were much higher than originally estimated.

Regulations may go forward before science and models are perfected because of the desire to mitigate the potential harm from environmental hazards. In the case of ozone modeling, the model inputs (emissions inventories in this case) are often more important than the model science (description of atmospheric transport and chemistry in this case) and require as careful an evaluation as the evaluation of the model. These factors point to the potential synergistic role that measurements play in model development and application.

In reality, all three categories are interrelated. Uncertainty in the underlying model structure or model framework uncertainty is the result of incomplete scientific data or lack of knowledge about the factors that control the behavior of the system being modeled. Model framework uncertainty can also be the result of simplifications needed to translate the conceptual model into mathematical terms as described in Section 3.3. In the scientific literature, this type of uncertainty is also referred to as structural error (Beck 1987), conceptual errors (Konikow and Bredehoeft 1992), uncertainties in the conceptual model (Usunoff et al. 1992), or model error/uncertainty (EPA 1997; Luis and McLaughlin 1992). Structural error relates to the mathematical construction of the algorithms that make up a model, while the conceptual model refers to the science underlying a model's governing equations. The terms "model error" and "model uncertainty" are both generally synonymous with model framework uncertainty.

Many models are developed iteratively to update their underlying science and resolve existing model framework uncertainty as new information becomes available. Models with long lives may undergo important changes from version to version. The MOBILE model for estimating atmospheric vehicle emissions, the CMAQ (Community Multi-scale Air Quality) model, and the QUAL2 water quality models are examples of models that have had multiple versions and major scientific modifications and extensions in over two decades of their existence (Scheffe and Morris 1993; Barnwell et al. 2004; EPA 1999c, as cited in NRC 2007).

When an appropriate model framework has been developed, the model itself may still be highly uncertain if the input data or database used to construct the application tool is not of sufficient quality. The quality of empirical data used for both model parameterization and corroboration tests is affected by both uncertainty and variability. This guidance uses the term "data uncertainty" to refer to the uncertainty caused by measurement errors, analytical imprecision, and limited sample sizes during data collection and treatment.

In contrast to data uncertainty, variability results from the inherent randomness of certain parameters, which in turn results from the heterogeneity and diversity in environmental processes. Examples of variability include fluctuations in ecological conditions, differences in habitat, and genetic variances among populations (EPA 1997). Variability in model parameters is largely dependent on the extent to which input data have been aggregated (both spatially and temporally). Data uncertainty is sometimes referred to as reducible uncertainty because it can be minimized with further study (EPA 1997). Accordingly, variability is referred to as irreducible because it can be better characterized and represented but not reduced with further study (EPA 1997).

A model's application niche is the set of conditions under which use of the model is scientifically defensible (EPA 1994b). Application niche uncertainty is therefore a function of the appropriateness of a model for use under a specific set of conditions. Application niche uncertainty is particularly important when (a) choosing among existing models for an application that lies outside the system for which the models were originally developed and/or (b) developing a larger model from several existing models with different spatial or temporal scales (Levins 1992).

The SAB's review of MMSOILS (Multimedia Contaminant Fate, Transport and Exposure Model) provides a good example of application niche uncertainty. The SAB questioned the adequacy of using a screening-level model to characterize situations where there is substantial subsurface heterogeneity or where non-aqueous phase contaminants are present (conditions differ from default values) (SAB 1993b). The SAB considered the MMSOILS model acceptable within its original application niche, but unsuitable for more heterogeneous conditions.

4.2.3.2 Model Corroboration

> *The interdependence of models and measurements is complex and iterative for several reasons. Measurements help to provide the conceptual basis of a model and inform model development, including parameter estimation. Measurements are also a critical tool for corroborating model results. Once developed, models can derive priorities for measurements that ultimately get used in modifying existing models or in developing new ones. Measurement and model activities are often conducted in isolation…Although environmental data systems serve a range of purposes, including compliance assessment, monitoring of trends in indicators, and basic research performance, the importance of models in the regulatory process requires measurements and models to be better integrated. Adaptive strategies that rely on iterations of measurements and modeling, such as those discussed in the 2003 NRC report titled* Adaptive Monitoring and Assessment for the Comprehensive Everglades Restoration Plan, *provide examples of how improved coordination might be achieved.*
>
> *— NRC Committee on Models in the Regulatory Decision Process (NRC 2007)*

Model corroboration includes all quantitative and qualitative methods for evaluating the degree to which a model corresponds to reality. The rigor of these methods varies depending on the type and purpose of the model application. Quantitative model corroboration uses statistics to estimate how closely the model results match measurements made in the real system. Qualitative corroboration activities may include expert elicitation to obtain beliefs about a system's behavior in a data-poor situation. These corroboration activities may move model forecasts toward consensus.

For newly developed model frameworks or untested mathematical processes, formal corroboration procedures may be appropriate. Formal corroboration may involve formulation of hypothesis tests for model acceptance, tests on datasets independent of the calibration dataset, and quantitative testing criteria. In many cases, collecting independent datasets for formal model corroboration is extremely costly or otherwise unfeasible. In such circumstances, model evaluation may be appropriately conducted using a combination of other evaluation tools discussed in this section.

Robustness is the capacity of a model to perform equally well across the full range of environmental conditions for which it was designed (Reckhow 1994; Borsuk et al. 2002). The degree of similarity among datasets available for calibration and corroboration provides insight into a model's robustness. For example, if the dataset used to corroborate a model is identical or statistically similar to the dataset used to calibrate the model, then the corroboration exercise has provided neither an independent measure of the model's performance nor insight into the model's robustness. Conversely, when corroboration data are significantly different from calibration data, the corroboration exercise provides a measure of both model performance and robustness.

Quantitative model corroboration methods are recommended for choosing among multiple models that are available for the same application. In such cases, models may be ranked on the basis of their statistical performance in comparison to the observational data (e.g., EPA 1992). EPA's Office of Air and Radiation evaluates models in this manner. When a single model is found to perform better than others in a given category, OAR recommends it in the *Guidelines on Air Quality Models* as a preferred model for application in that category (EPA 2003a). If models perform similarly, then the preferred model is selected based on other factors, such as past use, public familiarity, cost or resource requirements, and availability.

Box 8: Example: Comparing Results from Models of Varying Complexity
(From Box 5-4 in NRC's *Models in Environmental Regulatory Decision Making*)

The Clean Air Mercury Rule[6] requires industry to reduce mercury emissions from coal-fired power plants. A potential benefit is the reduced human exposure and related health impacts from methylmercury that may result from reduced concentrations of this toxin in fish. Many challenges and uncertainties affect assessment of this benefit. In its assessment of the benefits and costs of this rule, EPA used multiple models to examine how changes in atmospheric deposition would affect mercury concentrations in fish, and applied the models to assess some of the uncertainties associated with the model results (EPA 2005).

EPA based its national-scale benefits assessment on results from the mercury maps (MMaps) model. This model assumes a linear, steady-state relationship between atmospheric deposition of mercury and mercury concentrations in fish, and thus assumes that a 50% reduction in mercury deposition rates results in a 50% decrease in fish mercury concentrations. In addition, MMaps assumes instantaneous adjustment of aquatic systems and their ecosystems to changes in deposition — that is, no time lag in the conversion of mercury to methylmercury and its bioaccumulation in fish. MMaps also does not deal with sources of mercury other than those from atmospheric deposition. Despite those limitations, the Agency concluded that no other available model was capable of performing a national-scale assessment.

To further investigate fish mercury concentrations and to assess the effects of MMaps' assumptions, EPA applied more detailed models, including the spreadsheet-based ecological risk assessment for the fate of mercury (SERAFM) model, to five well-characterized ecosystems. Unlike the steady-state MMaps model, SERAFM is a dynamic model which calculates the temporal response of mercury concentrations in fish tissues to changes in mercury loading. It includes multiple land-use types for representing watershed loadings of mercury through soil erosion and runoff. SERAFM partitions mercury among multiple compartments and phases, including aqueous phase, abiotic participles (for example, silts), and biotic particles (for example, phytoplankton). Comparisons of SERAFM's predictions with observed fish mercury concentrations for a single fish species in four ecosystems showed that the model under-predicted mean concentrations for one water body, over-predicted mean concentrations for a second water body, and accurately predicted mean concentrations for the other two. The error bars for the observed fish mercury concentrations in these four ecosystems were large, making it difficult to assess the models' accuracy. Modeling the four ecosystems also showed how the assumed physical and chemical characteristics of the specific ecosystem affected absolute fish mercury concentrations and the length of time before fish mercury concentrations reached steady state.

Although EPA concluded that the best available science supports the assumption of a linear relationship between atmospheric deposition and fish mercury concentrations for broad-scale use, the more detailed ecosystem modeling demonstrated that individual ecosystems were highly sensitive to uncertainties in model parameters. The Agency also noted that many of the model uncertainties could not be quantified. Although the case studies covered the bulk of the key environmental characteristics, EPA found that extrapolating the individual ecosystem case studies to account for the variability in ecosystems across the country indicated that those case studies might not represent extreme conditions that could influence how atmospheric mercury deposition affected fish mercury concentrations in

---

[6] On February 8, 2008, the U.S. Court of Appeals for the District of Columbia Circuit vacated the Clean Air Mercury Rule. The DC Circuit's vacatur of this rule was unrelated to the modeling conducted in support of the rule.

a water body.

This example illustrates the usefulness of investigating a variety of models at varying levels of complexity. A hierarchical modeling approach, such as that used in the mercury analysis, can provide justification for simplified model assumptions or potentially provide evidence for a consistent bias that would negate the assumption that a simple model is appropriate for broad-scale application.

4.2.3.3 Sensitivity and Uncertainty Analysis

Sensitivity analysis is the study of how a model's response can be apportioned to changes in model inputs (Saltelli et al. 2000a). Sensitivity analysis is recommended as the principal evaluation tool for characterizing the most and least important sources of uncertainty in environmental models.

Uncertainty analysis investigates the lack of knowledge about a certain population or the real value of model parameters. Uncertainty can sometimes be reduced through further study and by collecting additional data. EPA guidance (e.g., EPA 1997) distinguishes uncertainty analysis from methods used to account for variability in input data and model parameters. As mentioned earlier, variability in model parameters and input data can be better characterized through further study but is usually not reducible (EPA 1997).

Although sensitivity and uncertainty analysis are closely related, sensitivity is algorithm-specific with respect to model "variables" and uncertainty is parameter-specific. Sensitivity analysis assesses the "sensitivity" of the model to specific parameters and uncertainty analysis assesses the "uncertainty" associated with parameter values. Both types of analyses are important to understand the degree of confidence a user can place in the model results. Recommended techniques for conducting uncertainty and sensitivity analysis are discussed in Appendix D.

The NRC committee pointed out that uncertainty analysis for regulatory environmental modeling involves not only analyzing uncertainty, but also communicating the uncertainties to policy makers. To facilitate communication of model uncertainty, the committee recommends using hybrid approaches in which unknown quantities are treated probabilistically *and* explored in scenario-assessment mode by decision makers through a range of plausible values. The committee further acknowledges (NRC 2007) that:

> *Effective uncertainty communication requires a high level of interaction with the relevant decision makers to ensure that they have the necessary information about the nature and sources of uncertainty and their consequences. Thus, performing uncertainty analysis for environmental regulatory activities requires extensive discussion between analysts and decision makers.*

4.3 Evaluating Proprietary Models

This guidance defines proprietary models as those computer models for which the source code is not universally shared. To promote the transparency with which decisions are made, EPA prefers using non-proprietary models when available. However, the Agency acknowledges there will be times when the use of proprietary models provides the most reliable and best-accepted characterization of a system.

When a proprietary model is used, its use should be accompanied by comprehensive, publicly available documentation. This documentation should describe:

- The conceptual model and the theoretical basis (as described in Section 3.3.1) for the model.
- The techniques and procedures used to verify that the proprietary model is free from numerical problems or "bugs" and that it truly represents the conceptual model (as described in Section 3.3.3).
- The process used to evaluate the model (as described in Section 4.2) and the basis for concluding that the model and its analytical results are of a quality sufficient to serve as the basis for a decision (as described in Section 4.1).
- To the extent practicable, access to input and output data such that third parties can replicate the model results.

4.4 Learning From Prior Experiences — Retrospective Analyses of Models

The NRC Committee on Models in the Regulatory Decision Process emphasized that the final issue in managing the model evaluation process is the learning that comes from examining prior modeling experiences. Retrospective analysis of models is important to individual models and regulatory policies and to systematically enhance the overall modeling field. The committee pointed out that retrospective analyses can be considered from various perspectives:

- They can investigate the systematic strengths and weaknesses that are characteristic of broad classes of models — for example, models of ground water flow, surface water, air pollution, and health risks assessment. For example, a researcher estimated that in 20 to 30 percent of ground water modeling efforts, surprising occurrences indicated that the conceptual model underlying the computer model was invalid (Bredehoeft 2003, 2005, in NRC 2007).

- They can study the processes (for example, approaches to model development and evaluation) that lead to successful model applications.

- They can examine models that have been in use for years to determine how well they work. Ongoing evaluation of the model against data, especially data taken under novel conditions, offers the best chance to identify and correct conceptual errors. This type of analysis is referred to as a model "post-audit" (see Section 5.5)

The results of retrospective evaluations of individual models and model classes can be used to identify priorities for improving models.

Box 9: Example of a Retrospective Model Analysis at EPA
(From Box 4-6 in NRC's *Models in Environmental Regulatory Decision Making*)

EPA's Model Evaluation and Applications Research Branch has been performing a retrospective analysis of the CMAQ model's ability to simulate the change in a pollutant associated with a known change in emissions (A. Gilliland, EPA, personal commun., May 19, 2006 and March 5, 2007). This study, which EPA terms a "dynamic evaluation" study, focuses on a rule issue by EPA in 1998 that required 22 states and the District of Columbia to submit State Implementation Plans providing NO_x emission reductions to mitigate ozone transport in the eastern United States. This rule, known as the NO_x SIP Call, requires emission reductions from the utility sector and large industrial boilers in the eastern and midwestern United States by 2004. Since theses sources are equipped with continuous emission monitoring systems, the NO_x SIP call represents a special opportunity to directly measure the emission changes and incorporate them into model simulations with reasonable confidence.

Air quality model simulations were developed for the summers of 2002 and 2004 using the CMAQ model, and the resulting ozone predictions were compared to observed ozone concentrations. Two series of CMAQ simulations were developed to test two different chemical mechanisms in CMAQ. This allowed an evaluation of the uncertainty associated with the model's representation of chemistry. Since the model's prediction of the relative change in pollutant concentrations provides input for regulatory decision making, this type of dynamic evaluations is particularly relevant to how the model is used.

4.5 Documenting the Model Evaluation

In its *Models in Environmental Regulatory Decision Making* report, the NRC summarizes the key elements of a model evaluation (NRC 2007). This list provides a useful framework for documenting the results of model evaluation as the various elements are conducted during model development and application:

- **Scientific basis.** The scientific theories that form the basis for models.
- **Computational infrastructure.** The mathematical algorithms and approaches used in executing the model computations.
- **Assumptions and limitations.** The detailing of important assumptions used in developing or applying a computational model, as well as the resulting limitations that will affect the model's applicability.
- **Peer review.** The documented critical review of a model or its application conducted by qualified individuals who are independent of those who performed the work, but who collectively have at least equivalent technical expertise to those who performed the original work. Peer review attempts to ensure that the model is technically adequate, competently performed, properly documented, and satisfies established quality requirements through the review of assumptions, calculations, extrapolations, alternate interpretations, methodology, acceptance criteria, and/or conclusions pertaining from a model or its application (modified from EPA 2006).
- **Quality assurance and quality control (QA/QC).** A system of management activities involving planning, implementation, documentation, assessment, reporting, and improvement to ensure that a model and its components are of the type needed and expected for its task and that they meet all required performance standards.
- **Data availability and quality.** The availability and quality of monitoring and laboratory data that can be used for both developing model input parameters and assessing model results.

- **Test cases.** Basic model runs where an analytical solution is available or an empirical solution is known with a high degree of confidence to ensure that algorithms and computational processes are implemented correctly.
- **Corroboration of model results with observations.** Comparison of model results with data collected in the field or laboratory to assess the model's accuracy and improve its performance.
- **Benchmarking against other models.** Comparison of model results with other similar models.
- **Sensitivity and uncertainty analysis.** Investigation of the parameters or processes that drive model results, as well as the effects of lack of knowledge and other potential sources of error in the model.
- **Model resolution capabilities.** The level of disaggregation of processes and results in the model compared to the resolution needs from the problem statement or model application. The resolution includes the level of spatial, temporal, demographic, or other types of disaggregation.
- **Transparency.** The need for individuals and groups outside modeling activities to comprehend either the processes followed in evaluation or the essential workings of the model and its outputs.

4.6 Deciding Whether to Accept the Model for Use in Decision Making

The model development and evaluation process culminates in a decision to accept (or not accept) the model for use in decision making. This decision is made by the program manager charged with making regulatory decisions, in consultation with the model developers and project team. It should be informed by good communication of the key findings of the model evaluation process, including the critical issue of uncertainty. The project team should gain model acceptance before applying the model to decision making to avoid confusion and potential re-work.

5. Model Application

5.1 Introduction

Once a model has been accepted for use by decision makers, it is applied to the problem that was identified in the first stages of the modeling process. Model application commonly involves a shift from the *hindcasting* (testing the model against past observed conditions) used in the model development and evaluation phases to *forecasting* (predicting a future change) in the application phase. This may involve a collaborative effort between modelers and program staff to devise management scenarios that represent different regulatory alternatives. Some model applications may entail trial-and-error model simulations, where model inputs are changed iteratively until a desired environmental condition is achieved.

Using a model in a proposed decision requires that the model application be transparently incorporated into the public process. This is accomplished by providing written documentation of the model's relevant characteristics in a style and format accessible to the interested public, and by sharing specific model files and data with external parties, such as technical consultants and university scientists, upon request. This chapter presents best practices and other recommendations for integrating the results of environmental models into Agency decisions. Section 5.2 describes how to achieve and document a transparent modeling process, Section 5.3 reviews situations when use of multiple models may be appropriate, and Section 5.4 discusses the use of post-audits to determine whether the actual system response concurs with that predicted by the model.

Box 10: Examples of Major EPA Documents That Incorporate a Substantial Amount of Computational Modeling Activities
(From Table 2-2 in NRC's *Models in Environmental Regulatory Decision Making*)

Air Quality
Criteria Documents and Staff Paper for Establishing NAAQS
Summarize and assess exposures and health impacts for the criteria air pollutants (ozone, particulate matter, carbon monoxide, lead, nitrogen dioxide, and sulfur dioxide). Criteria documents include results from exposure and health modeling studies, focusing on describing exposure-response relationships. For example, the particulate matter criteria document placed emphasis on epidemiological models of morbidity and mortality (EPA 2004c). The Staff Paper takes this scientific foundation a step further by identifying the crucial health information and using exposure modeling to characterize risks that serve as the basis for the staff recommendation of the standards to the EPA Administrator. For example, models of the number of children exercising outdoors during those parts of the day when ozone is elevated had a major influence on decisions about the 8-hour ozone national ambient air quality standard (EPA 1996).
State Implementation Plan (SIP) Amendments
A detailed description of the scientific methods and emissions reduction programs a state will use to carry out its responsibilities under the CAA for complying with NAAQS. A SIP typically relies on results from activity, emissions, and air quality modeling. Model-generated emissions inventories serve as input to regional air quality models and are used to test alternative emission-reduction schemes to see whether they will result in air quality standards being met (e.g., ADEC 2001; TCEQ 2004). Regional-scale modeling has become part of developing state implementation plans

for the new 8-hour ozone and fine particulate matter standards. States, local governments, and their consultants do this analysis.

Regulatory Impact Assessments (RIAs) for Air Quality Rules

RIAs for air quality regulations document the costs and benefits of major emission control regulations. Recent RIAs have included emissions, air quality, exposure, and health and economic impacts modeling results (e.g., EPA 2004b)

Water Regulations

Total Maximum Daily Load (TMDL) Determinations

For each impaired water body, a TMDL identifies (a) the water quality standard that is not being attained and the pollutant causing the impairment (b) and the total loading of the pollutant that the water may receive and still meet the water quality standard and (c) allocates that total loading among the point and nonpoint sources of the pollutant discharging to the water. Establishment of TMDLs may utilize water quality and/or nutrient loading models. States establish most TMDLs and therefore state and their consultants can be expected to do the majority of this modeling, with EPA occasionally doing the modeling for particularly contentious TMDLs (EPA 2002b; George 2004; Shoemaker 2004; Wool 2004).

Leaking Underground Storage Tank Program

Assesses the potential risks associated with leaking underground gasoline storage tanks. At an initial screening level, it may assess one-dimensional transport of a conservative contaminant using an analytical model (Weaver 2004).

Development of Maximum Contaminant Levels for Drinking Water

Assess drinking water standards for public water supply systems. Such assessments can include exposure, epidemiology, and dose-response modeling (EPA 2002c; NRC 2001b, 2005b).

Pesticides and Toxic Substances Program

Pre-manufacturing Notice Decisions

Assess risks associated with new manufactured chemicals entering the market. Most chemicals are screened initially as to their environmental and human health risks using structure-activity relationship models.

Pesticide Reassessments

Requires that all existing pesticides undergo a reassessment based on cumulative (from multiple pesticides) and aggregate (exposure from multiple pathways) health risk. This includes the use of pesticide exposure models.

Solid and Hazardous Wastes Regulations

Superfund Site Decision Documents

Includes the remedial investigation, feasibility study, proposed plan, and record-of-decision documents that address the characteristics and cleanup of Superfund sites. For many hazardous waste sites, a primary modeling task is using groundwater modeling to assess movement of toxic substances through the substrate (Burden 2004). The remedial investigation for a mining megasite might include water quality, environmental chemistry, human health risk, and ecological risk assessment modeling (NRC 2005a).

Human Health Risk Assessment

Benchmark Dose (BMD) Technical Guidance Document

EPA relies on both laboratory animal and epidemiological studies to assess the noncancer effects of chronic exposure to pollutants (that is, the reference dose [RfD] and the inhalation reference concentration, [RfC]). These data are modeled to estimate the human dose-response. EPA recommends the use of BMD modeling, which essentially fits the experimental data to use as much of the available data as possible (EPA 2000).

Ecological Risk Assessment

The ecological risk assessment guidelines provide general principles and give examples to show how ecological risk assessment can be applied to a wide range of systems, stressors, and biological, spatial, and temporal scales. They describe the strengths and limitations of alternative approaches and emphasize processes and approaches for analyzing data rather than specifying data collection techniques, methods or models (EPA 1998).

5.2 Transparency

The objective of transparency is to enable communication between modelers, decision makers, and the public. Model transparency is achieved when the modeling processes are documented with clarity and completeness at an appropriate level of detail. When models are transparent, they can be used reasonably and effectively in a regulatory decision.

5.2.1 Documentation

Documentation enables decision makers and other model users to understand the process by which a model was developed and used. During model development and use, many choices must be made and options selected that may bias the model results. Documenting this process and its limitations and uncertainties is essential to increase the utility and acceptability of the model outcomes. Modelers and project teams should document all relevant information about the model to the extent practicable, particularly when a controversial decision is involved. In legal proceedings, the quality and thoroughness of the model's written documentation and the Agency's responses to peer review and public comments on the model can affect the outcome of the legal challenge.

The documentation should include a clear explanation of the model's relationship to the scenario of the particular application. This explanation should describe the limitations of the available information when applied to other scenarios. Disclosure about the state of science used in a model and future plans to update the model can help establish a record of reasoned, evidence-based application to inform decisions. For example, EPA successfully defended a challenge to a model used in its TMDL program when it explained that it was basing its decision on the best available scientific information and that it intended to refine its model as better information surfaced.[7]

When a court reviews EPA modeling decisions, they generally give some deference to EPA's technical expertise, unless it is without substantial basis in fact. As discussed in Section 4.2.3 regarding corroboration, deviations from empirical observations are to be expected. In substantive legal disputes, the courts generally examine the record supporting EPA's decisions for justification as to why the model was reasonable.[8] The record should contain not only model development, evaluation, and application but also the Agency's responses to comments on the model raised during peer review and the public process. The organization of this guidance document offers a general outline for model documentation. Box 11 provides a more detailed outline. These elements are adapted from EPA Region 10's standard practices for modeling projects.

[7] *Natural Resources Defense Council v. Muszynski*, 268 F.3d 91 (2d Cir. 2001).
[8] *American Iron and Steel Inst. v. EPA*, 115 F.3d 979 (D.C. Cir. 1997).

Box 11: Recommended Elements for Model Documentation

1. Management Objectives
- Scope of problem
- Technical objectives that result from management objectives
- Level of analysis needed
- Level of confidence needed

2. Conceptual Model
- System boundaries (spatial and temporal domain)
- Important time and length scales
- Key processes
- System characteristics
- Source description
- Available data sources (quality and quantity)
- Data gaps
- Data collection programs (quality and quantity)
- Mathematical model
- Important assumptions

3. Choice of Technical Approach
- Rationale for approach in context of management objectives and conceptual model
- Reliability and acceptability of approach
- Important assumptions

4. Parameter Estimation
- Data used for parameter estimation
- Rationale for estimates in the absence of data
- Reliability of parameter estimates

5. Uncertainty/Error
- Error/uncertainty in inputs, initial conditions, and boundary conditions
- Error/uncertainty in pollutant loadings
- Error/uncertainty in specification of environment
- Structural errors in methodology (e.g., effects of aggregation or simplification)

6. Results
- Tables of all parameter values used for analysis
- Tables or graphs of all results used in support of management objectives or conclusions
- Accuracy of results

7. Conclusions of analysis in relationship to management objectives

8. Recommendations for additional analysis, if necessary

Note: The QA project plan for models (EPA 2002b) *includes a documentation and records component that also describes the types of records and level of detailed documentation to be kept depending on the scope and magnitude of the project.*

5.2.2 Effective Communication

The modeling process should effectively communicate uncertainty to anyone interested in the model results. All technical information should be documented in a manner that decision makers and stakeholders can readily interpret and understand. Recommendations for improving clarity, adapted from the Risk Characterization Handbook (EPA 2000d), include the following:

- Be as brief as possible while still providing all necessary details.

- Use plain language that modelers, policy makers, and the informed lay person can understand.
- Avoid jargon and excessively technical language. Define specialized terms upon first use.
- Provide the model equations.
- Use clear and appropriate methods to efficiently display mathematical relationships.
- Describe quantitative outputs clearly.
- Use understandable tables and graphics to present technical data (see Morgan and Henrion, 1990, for suggestions).

The conclusions and other key points of the modeling project should be clearly communicated. The challenge is to characterize these essentials for decision makers, while also providing them with more detailed information about the modeling process and its limitations. Decision makers should have sufficient insight into the model framework and its underlying assumptions to be able to apply model results appropriately. This is consistent with QA planning practices that assert that all technical reports must discuss the data quality and any limitations with respect to their intended use (EPA 2000e).

5.3 Application of Multiple Models

As mentioned in earlier chapters, multiple models sometimes apply to a certain decision making need; for example, several air quality models, each with its own strengths and weaknesses, might be applied for regulatory purposes. In other situations, stakeholders may use alternative models (developed by industry and academic researchers) to produce alternative risk assessments (e.g., CARES pesticide exposure model developed by industry). One approach to address this issue is to use multiple models of varying complexities to simulate the same phenomena (NRC 2007). This may provide insight into how sensitive the results are to different modeling choices and how much trust to put in the results from any one model. Experience has shown that running multiple models can increase confidence in the model results (Manno et al. 2008) (see Box 8 in Chapter 4 for an example). However, resource limitations or regulatory time constraints may limit the capacity to fully evaluate all possible models.

5.4 Model Post-Audit

Due to time complexity, constraints, scarcity of resources, and/or lack of scientific understanding, technical decisions are often based on incomplete information and imperfect models. Further, even if model developers strive to use the best science available, scientific knowledge and understanding are continually advancing. Given this reality, decision makers should use model results in the context of an iterative, ever-improving process of continuous model refinement to demonstrate the accountability of model-based decisions. This process includes conducting model post-audits to assess and improve a model and its ability to provide valuable predictions for management decisions. Whereas corroboration (discussed in Section 4.2.3.2) demonstrates the degree to which a model corresponds to past system behavior, a model post-audit assesses its ability to model future conditions (Anderson and Woessner 1992).

A model post-audit involves monitoring the modeled system, after implementing a remedial or management action, to determine whether the actual system response concurs with that predicted by the model. Post-auditing of all models is not feasible due to resource constraints, but targeted audits of commonly used models may provide valuable information for improving model frameworks and/or model parameter estimates. In its review of the TMDL program, the NRC recommended that EPA implement this approach by selectively targeting “some post-implementation TMDL compliance monitoring for verification data collection to assess model prediction error” (NRC 2001). The post-audit should also evaluate how effectively the model development and use process engaged decision makers and other stakeholders (Manno et al. 2008).

Appendix A: Glossary of Frequently Used Terms

Accuracy: The closeness of a measured or computed value to its "true" value, where the "true" value is obtained with perfect information. Due to the natural heterogeneity and stochasticity of many environmental systems, this "true" value exists as a distribution rather than a discrete value. In these cases, the "true" value will be a function of spatial and temporal aggregation.

Algorithm: A precise rule (or set of rules) for solving some problem.

Analytical model: A model that can be solved mathematically in terms of analytical functions. For example, some models that are based on relatively simple differential equations can be solved analytically by combinations of polynomials, exponential, trigonometric, or other familiar functions.

Applicability and utility: One of EPA's five assessment factors (see definition) that describes the extent to which the information is relevant for the Agency's intended use (EPA 2003b).

Application niche: The set of conditions under which the use of a model is scientifically defensible. The identification of application niche is a key step during model development. Peer review should include an evaluation of application niche. An explicit statement of application niche helps decision makers understand the limitations of the scientific basis of the model (EPA 1993).

Application niche uncertainty: Uncertainty as to the appropriateness of a model for use under a specific set of conditions (see "application niche").

Assessment factors: Considerations recommended by EPA for evaluating the quality and relevance of scientific and technical information. The five assessment factors are soundness, applicability and utility, clarity and completeness, uncertainty and variability, and evaluation and review (EPA 2003b).

Bias: Systemic deviation between a measured (i.e., observed) or computed value and its "true" value. Bias is affected by faulty instrument calibration and other measurement errors, systemic errors during data collection, and sampling errors such as incomplete spatial randomization during the design of sampling programs.

Boundaries: The spatial and temporal conditions and practical constraints under which environmental data are collected. Boundaries specify the area or volume (spatial boundary) and the time period (temporal boundary) to which a model application will apply (EPA 2000a).

Boundary conditions: Sets of values for state variables and their rates along problem domain boundaries, sufficient to determine the state of the system within the problem domain.

Calibration: The process of adjusting model parameters within physically defensible ranges until the resulting predictions give the best possible fit to the observed data (EPA 1994b). In some disciplines, calibration is also referred to as "parameter estimation" (Beck et al. 1994).

Checks: Specific tests in a quality assurance plan that are used to evaluate whether the specifications (performance criteria) for the project developed at its onset have been met.

Clarity and completeness: One of EPA's five assessment factors (see definition) that describes the degree of clarity and completeness with which the data, assumptions, methods, quality assurance, sponsoring organizations, and analyses employed to generate the information are documented (EPA 2003b).

Class (see "object-oriented platform"): A set of objects that share a common structure and behavior. The structure of a class is determined by the class variables, which represent the state of an object of that class; the behavior is given by the set of methods associated with the class (Booch 1994).

Code: Instructions, written in the syntax of a computer language, that provide the computer with a logical process. "Code" can also refer to a computer program or subset. The term "code" describes the fact that computer languages use a different vocabulary and syntax than algorithms that may be written in standard language.

Code verification: Examination of the algorithms and numerical technique in the computer code to ascertain that they truly represent the conceptual model and that there are no inherent numerical problems with obtaining a solution (Beck et al. 1994).

Complexity: The opposite of simplicity. Complex systems tend to have a large number of variables, multiple parts, and mathematical equations of a higher order, and to be more difficult to solve. Used to describe computer models, "complexity" generally refers to the level in difficulty in solving mathematically posed problems as measured by the time, number of steps or arithmetic operations, or memory space required (called time complexity, computational complexity, and space complexity, respectively).

Computational models: Models that use measurable variables, numerical inputs, and mathematical relationships to produce quantitative outputs.

Conceptual basis: An underlying scientific foundation of model algorithms or governing equations. The conceptual basis for a model is either empirical (based on statistical relationships between observations) or mechanistic (process-based) or a combination. See definitions for "empirical model" and "mechanistic model."

Conceptual model: A hypothesis regarding the important factors that govern the behavior of an object or process of interest. This can be an interpretation or working description of the characteristics and dynamics of a physical system (EPA 1994b).

Confounding error: An error induced by unrecognized effects from variables that are not included in the model. The unrecognized, uncharacterized nature of these errors makes them more difficult to describe and account for in statistical analysis of uncertainty (Small and Fishbeck 1999).

Constant: A fixed value (e.g., the speed of light, the gravitational force) representing known physical, biological, or ecological activities.

Corroboration (model): Quantitative and qualitative methods for evaluating the degree to which a model corresponds to reality. In some disciplines, this process has been referred to as validation. In general, the term "corroboration" is preferred because it implies a claim of usefulness and not truth.

Data uncertainty: Uncertainty (see definition) that is caused by measurement errors, analytical imprecision, and limited sample sizes during the collection and treatment of data. Data uncertainty, in contrast to variability (see definition), is the component of total uncertainty that is "reducible" through further study.

Debugging: The identification and removal of bugs from computer code. Bugs are errors in computer code that range from typos to misuse of concepts and equations.

Deterministic model: A model that provides a solution for the state variables rather than a set of probabilistic outcomes. Because this type of model does not explicitly simulate the effects of data uncertainty or variability, changes in model outputs are solely due to changes in model components or in the boundary conditions or initial conditions.

Domain (spatial and temporal): The spatial and temporal domains of a model cover the extent and resolution with respect to space and time for which the model has been developed and over which it should be evaluated.

Domain boundaries (spatial and temporal): The limits of space and time that bound a model's domain and are specified within the boundary conditions (see "boundary conditions").

Dynamic model: A model providing the time-varying behavior of the state variables.

Empirical model: A model whose structure is determined by the observed relationship among experimental data (Suter 1993). These models can be used to develop relationships that are useful for forecasting and describing trends in behavior, but they are not necessarily mechanistically relevant.

Environmental data: Information collected directly from measurements, produced from models, and compiled from other sources such as databases and literature (EPA 2002a).

Evaluation and review: One of EPA's five assessment factors (see definition) that describes the extent of independent verification, validation, and peer review of the information or of the procedures, measures, methods, or models (EPA 2003b).

Expert elicitation: A systematic process for quantifying, typically in probabilistic terms, expert judgments about uncertain quantities. Expert elicitation can be used to characterize uncertainty and fill data gaps where traditional scientific research is not feasible or data are not yet available. Typically, the necessary quantities are obtained through structured interviews and/or questionnaires. Procedural steps can be used to minimize the effects of heuristics and bias in expert judgments.

Extrapolation: Extrapolation is a process that uses assumptions about fundamental causes underlying the observed phenomena in order to project beyond the range of the data. In general, extrapolation is not considered a reliable process for prediction; however, there are situations where it may be necessary and useful.

False negative: Also known as a false acceptance decision errors, a false negative occurs when the null hypothesis or baseline condition cannot be rejected based on the available sample data. The decision is made assuming the baseline condition is true when in reality it is false (EPA 2000a).

False positive: Also known as a false rejection decision error, a false positive occurs when the null hypothesis or baseline condition is incorrectly rejected based on the sample data. The decision is made assuming the alternate condition or hypothesis to be true when in reality it is false (EPA 2000a).

Forcing/driving variable: An external or exogenous (from outside the model framework) factor that influences the state variables calculated within the model. Such variables include, for example, climatic or environmental conditions (temperature, wind flow, oceanic circulation, etc.).

Forms (models): Models can be represented and solved in different forms, including analytic, stochastic, and simulation.

Function: A mathematical relationship between variables.

Graded approach: The process of basing the level of application of managerial controls to an item or work on the intended use of results and degree of confidence needed in the results (EPA 2002b).

Integrity: One of three main components of quality in EPA's Information Quality Guidelines. "Integrity" refers to the protection of information from unauthorized access or revision to ensure that it is not compromised through corruption or falsification (EPA 2002a).

Intrinsic variation: The variability (see definition) or inherent randomness in the real-world processes.

Loading: The rate of release of a constituent of interest to a particular receiving medium.

Measurement error: An error in the observed data caused by human or instrumental error during collection. Such errors can be independent or random. When a persistent bias or mis-calibration is present in the measurement device, measurement errors may be correlated among observations (Small and Fishbeck 1999). In some disciplines, measurement error may be referred to as observation error.

Mechanistic model: A model whose structure explicitly represents an understanding of physical, chemical, and/or biological processes. Mechanistic models quantitatively describe the relationship between some phenomenon and underlying first principles of cause. Hence, in theory, they are useful for inferring solutions outside the domain in which the initial data were collected and used to parameterize the mechanisms.

Mode (of a model): The manner in which a model operates. Models can be designed to represent phenomena in different modes. Prognostic (or predictive) models are designed to forecast outcomes and future events, while diagnostic models work "backwards" to assess causes and precursor conditions.

Model: A simplification of reality that is constructed to gain insights into select attributes of a physical, biological, economic, or social system. A formal representation of the behavior of system processes, often in mathematical or statistical terms. The basis can also be physical or conceptual (NRC 2007).

Model coding: The process of translating the mathematical equations that constitute the model framework into a functioning computer program.

Model evaluation: The process used to generate information to determine whether a model and its results are of a quality sufficient to serve as the basis for a regulatory decision.

Model framework: The system of governing equations, parameterization, and data structures that make up the mathematical model. The model framework is a formal mathematical specification of the concepts and procedures of the conceptual model consisting of generalized algorithms (computer code/software) for different site- or problem-specific simulations (EPA 1994b).

Model framework uncertainty: The uncertainty in the underlying science and algorithms of a model. Model framework uncertainty is the result of incomplete scientific data or lack of knowledge about the factors that control the behavior of the system being modeled. Model framework uncertainty can also be the result of simplifications necessary to translate the conceptual model into mathematical terms.

Module: An independent or self-contained component of a model, which is used in combination with other components and forms part of one or more larger programs.

Noise: Inherent variability that the model does not characterize (see definition for variability).

Objectivity: One of three main components of quality in EPA's Information Quality Guidelines. It includes whether disseminated information is being presented in an accurate, clear, complete and unbiased manner. In addition, objectivity involves a focus on ascertaining accurate, reliable, and unbiased information (EPA 2002a).

Object-oriented platform: A type of user interface that models systems using a collection of cooperating "objects." These objects are treated as instances of a class within a class hierarchy

Parameters: Terms in the model that are fixed during a model run or simulation but can be changed in different runs as a method for conducting sensitivity analysis or to achieve calibration goals.

Parameter uncertainty: Uncertainty (see definition) related to parameter values.

Parametric variation: When the value of a parameter itself is not a constant and includes natural variability. Consequently, the parameter should be described as a distribution (Shelly et al. 2000).

Perfect information: The state of information where in which there is no uncertainty. The current and future values for all parameters are known with certainty. The state of perfect information includes knowledge about the values of parameters with natural variability.

Precision: The quality of being reproducible in amount or performance. With models and other forms of quantitative information, “precision” refers specifically to the number of decimal places to which a number is computed as a measure of the “preciseness” or “exactness” with which a number is computed.

Probability density function: Mathematical, graphical, or tabular expression of the relative likelihoods with which an unknown or variable quantity may take various values. The sum (or integral) of all likelihoods equals 1 for discrete (continous) random variables (Cullen and Frey 1999). These distributions arise from the fundamental properties of the quantities we are attempting to represent. For example, quantities formed from adding many uncertain parameters tend to be normally distributed, and quantities formed from multiplying uncertain quantities tend to be lognormal (Morgan and Henrion 1990).

Program (computer): A set of instructions, written in the syntax of a computer language, that provide the computer with a step-by-step logical process. Computer programs are also referred to as code.

Qualitative assessment: Some of the uncertainty in model predictions may arise from sources whose uncertainty cannot be quantified. Examples are uncertainties about the theory underlying the model, the manner in which that theory is mathematically expressed to represent the environmental components, and the theory being modeled. The subjective evaluations of experts may be needed to determine appropriate values for model parameters and inputs that cannot be directly observed or measured (e.g., air emissions estimates). Qualitative corroboration activities may involve the elicitation of expert judgment on the true behavior of the system and agreement with model-forecasted behavior.

Quality: A broad term that includes notions of integrity, utility, and objectivity (EPA 2002a).

Quantitative assessment: The uncertainty in some sources — such as some model parameters and some input data — can be estimated through quantitative assessments involving statistical uncertainty and sensitivity analyses. In addition, comparisons can be made for the special purpose of quantitatively describing the differences to be expected between model estimates of current conditions and comparable field observations.

Reducible uncertainty: Uncertainty in models that can be minimized or even eliminated with further study and additional data (EPA 1997). See “data uncertainty.“

Quality: A broad term that includes notions of integrity, utility, and objectivity (USEPA 2002a).
Reducible Uncertainty: Uncertainty in models that can be minimized or even eliminated with further study and additional data (USEPA 1997). See data uncertainty.

Reliability: The confidence that (potential) users have in a model and in the information derived from the model such that they are willing to use the model and the derived information (Sargent 2000). Specifically, reliability is a function of the performance record of a model and its conformance to best available, practicable science.

Response surface: A theoretical multi-dimensional “surface” that describes the response of a model to changes in its parameter values. A response surface is also known as a sensitivity surface.

Robustness: The capacity of a model to perform well across the full range of environmental conditions for which it was designed.

Screening model: A type of model designed to provide a “conservative” or risk-averse answer. Screening models can be used with limited information and are conservative, and in some cases they can be used in lieu of refined models, even when time or resources are not limited.

Sensitivity: The degree to which the model outputs are affected by changes in selected input parameters (Beck et al. 1994).

Sensitivity analysis: The computation of the effect of changes in input values or assumptions (including boundaries and model functional form) on the outputs (Morgan and Henrion 1990); the study of how uncertainty in a model output can be systematically apportioned to different sources of uncertainty in the model input (Saltelli et al. 2000a). By investigating the “relative sensitivity” of model parameters, a user can become knowledgeable of the relative importance of parameters in the model.

Simulation model: A model that represents the development of a solution by incremental steps through the model domain. Simulations are often used to obtain solutions for models that are too complex to be solved analytically. For most situations, where a differential equation is being approximated, the simulation model will use finite time step (or spatial step) to “simulate” changes in state variables over time (or space).

Soundness: One of EPA’s five assessment factors (see definition) that describes the extent to which the scientific and technical procedures, measures, methods, or models employed to generate the information are reasonable for and consistent with the intended application (EPA 2003b).

Specifications: Acceptance criteria set at the onset of a quality assurance plan that help to determine if the intended objectives of the project have been met. Specifications are evaluated using a series of associated checks (see definition).

State variables: The dependent variables calculated within a model, which are also often the performance indicators of the models that change over the simulation.

Statistical model: A model built using observations within a probabilistic framework. Statistical models include simple linear or multivariate regression models obtained by fitting observational data to a mathematical function.

Steady-state model: A model providing the long-term or time-averaged behavior of the state variables.

Stochasticity: Fluctuations in ecological processes that are due to natural variability and inherent randomness.

Stochastic model: A model that includes variability (see definition) in model parameters. This variability is a function of changing environmental conditions, spatial and temporal aggregation within the model framework, and random variability. The solution obtained by the model or output is therefore a function of model components and random variability.

Transparency: The clarity and completeness with which data, assumptions, and methods of analysis are documented. Experimental replication is possible when information about modeling processes is properly and adequately communicated (EPA 2002a).

Uncertainty: The term used in this document to describe lack of knowledge about models, parameters, constants, data, and beliefs. There are many sources of uncertainty, including the science underlying a model, uncertainty in model parameters and input data, observation error, and code uncertainty. Additional study and collecting more information allows error that stems from uncertainty to be minimized/reduced (or eliminated). In contrast, variability (see definition) is irreducible but can be better characterized or represented with further study (EPA 2002b, Shelly et al. 2000).

Uncertainty analysis: Investigation of the effects of lack of knowledge or potential errors on the model (e.g, the "uncertainty" associated with parameter values). When combined with sensitivity analysis (see definition), uncertainty analysis allows a model user to be more informed about the confidence that can be placed in model results.

Uncertainty and variability: One of EPA's five assessment factors (see definition) that describes the extent to which the variability and uncertainty (quantitative and qualitative) in the information or in the procedures, measures, methods, or models are evaluated and characterized (EPA 2003b).

Utility: One of three main components of quality in EPA's Information Quality Guidelines. "Utility" refers to the usefulness of the information to the intended users (EPA 2002a).

Variable: A measured or estimated quantity that describes an object or can be observed in a system and that is subject to change.

Variability: Observed differences attributable to true heterogeneity or diversity. Variability is the result of natural random processes and is usually not reducible by further measurement or study (although it can be better characterized) (EPA 1997).

Verification (code): Examination of the algorithms and numerical technique in the computer code to ascertain that they truly represent the conceptual model and that there are no inherent numerical problems with obtaining a solution (Beck et al 1994).

Appendix B: Categories of Environmental Regulatory Models

This section is taken from Appendix C of the NRC report Models in Environmental Regulatory Decision Making.

Models can be categorized according to their fit into a continuum of processes that translate human activities and natural systems interactions into human health and environmental impacts. The categories of models that are integral to environmental regulation include human activity models, natural systems models, emissions models, fate and transport models, exposure models, human health and environmental response models, economic impact models, and noneconomic impact models. Examples of models in each of these categories are discussed below.

HUMAN ACTIVITY MODELS

Anthropogenic emissions to the environment are inherently linked to human activities. Activity models simulate the human activities and behaviors that result in pollutants. In the environmental regulatory modeling arena, examples of modeled activities are the following:

- Demographic information, such as the magnitude, distribution, and dynamics of human populations, ranging from national growth projections to local travel activity patterns on the order of hours.
- Economic activity, such as the macroeconomic estimates of national economic production and income, final demands for aggregate industrial sectors, prices, international trade, interest rates, and financial flows.
- Human consumption of resources, such as gasoline or feed, may be translated into pollutant releases, such as nitrogen oxides or nutrients. Human food consumption is also used to estimate exposure to pollutants such as pesticides. Resource consumption in dollar terms may be used to assess economic impacts.
- Distribution and characteristics of land use are used to assess habitat, impacts on the hydrogeologic cycle and runoff, and biogenic pollutant releases.

Model	Type	Use	Additional Information
TRANSCAD, TRANSPLAN, MINUTP	Travel demand forecasting models	Develops estimation of motor vehicle miles traveled for use in estimating vehicle emissions. Can be combined with geographic information systems (GIS) for providing spatial and temporal distribution of motor vehicle activity.	http://www.caliper.com/tcvou.htm
DRI	Forecasts national economic indicators	Model can forecast over 1,200 economic concepts including aggregate supply, demand, prices, incomes, international trade, interest rates, etc. The eight sectors of the model are: domestic spending, domestic income, tax sector, prices, financial, international trade, expectations, and aggregate supply.	EIA 1993
E-GAS	National and regional economic activity model	Emissions growth factors for various sector for estimating volatile organic compounds, nitrogen oxides, and carbon monoxide emissions.	Young et al. 1994
YIELD	Crop-growth yield model	Predicts temporal and spatial crop yield.	Hayes et al. 1982

NATURAL SYSTEMS PROCESS AND EMISSIONS MODELS

Natural systems process and emissions models simulate the dynamics of ecosystems that directly or indirectly give rise to fluxes of nutrients and other environmental emissions.

Model	Type	Use	Additional Information
Marine Biological Laboratory General Ecosystem Model (MBL-GEM)	Pilot-scale nutrient cycling of carbon and nitrogen	Simulates plot-level photosynthesis and nitrogen uptake by plants, allocation of carbon and nitrogen to foliage, stems, and fine roots, respiration in these tissues, turnover of biomass through litter fall, and decomposition of litter and soil organic matter.	http://ecosystems.mbl.edu/Research/Models/gem/welcome.html
BEIS	Natural emissions of volatile organic compounds	Simulates nitric oxide emissions from soils and volatile organic compound emissions from vegetation. Input to grid models for NAAQS attainment (CAA)	http://www.epa.gov/asmdnerl/biogen.html
Natural Emissions Model	Natural emissions of methane and nitrous oxide	Models methane and nitrous oxide emissions from the terrestrial biosphere to atmosphere.	http://web.mit.edu/globalchange/www/tem.html#nem

EMISSIONS MODELS

These models estimate the rate or the amount of pollutant emissions to water bodies and the atmosphere. The outputs of emission models are used to generate inventories of pollutant releases that can then serve as an input to fate and transport models.

Model	Type	Use	Additional Information
PLOAD	Releases to water bodies	GIS bulk loading model providing annual pollutant loads to waterbodies. Conducts simplified analyses of sediment issues, including a bank erosion hazard index.	http://www.epa.gov/ost/basins
SPARROW	Releases to water bodies	Relates nutrient sources and watershed characteristics to total nitrogen. Predicts contaminant flux, concentration, and yield in streams. Provides empirical estimates (including uncertainties) of the fate of contaminants in streams.	http://water.usgs.gov/nawqa/sparrow
MOBILE MOVES NONROAD	Releases to air	Factors and activities for anthropogenic emissions from mobile sources. Estimates current and future emissions (hydrocarbons, carbon monoxide, nitrogen oxides, particulate matter, hazardous air pollutants, and carbon dioxide) from highway motor vehicles. Model used to evaluate mobile source control strategies, control strategies for state implementation plans, and for developing environmental impact statements, in addition to other research.	http://www.epa.gov/otaq/m6.htm http://www.epa.gov/otaq/nonrdmdl.htm EPA 2004, EPA 2005a, Glover and Cumberworth 2003

FATE AND TRANSPORT MODELS

Fate and transport models calculate the movement of pollutants in the environment. A large number of EPA models fall into this category. They are further categorized into the transport media they represent: subsurface, air, and surface water. In each medium, there are a range of models with respect to their complexity, where the level of complexity is a function of the following:

- The number of physical and chemical processes considered.
- The mathematical representation of those processes and their numerical solution.
- The spatial and temporal scales over which the processes are modeled.

Even though some fate and transport models can be statistical models, the majority is mechanistic (also referred to as process-based models). Such models simulate individual components in the system and the mathematical relationships among the components. Fate and transport model output has traditionally been deterministic, although recent focus on uncertainty and variability has led to some probabilistic models.

Subsurface Models

Subsurface transport is governed by the heterogeneous nature of the ground, the degree of saturation of the subsurface, as well as the chemical and physical properties of the pollutants of interest. Such models are used to assess the extent of toxic substance spills. They can also assess the fate of contaminants in sediments. The array of subsurface models is tailored to particular application objectives, for example, assessing the fate of contaminants leaking from underground gasoline storage tanks or leaching from landfills. Models are used extensively for site-specific risk assessments; for example, to determine pollutant concentrations in drinking-water sources. The majority of models simulate liquid pollutants; however, some simulate gas transport in the subsurface.

Model	Type	Use	Additional Information
MODFLOW	3D finite difference for ground water transport	Risk Assessments (RBCA) Superfund Remediation (CERCLA). Modular three-dimensional model that simulates ground water flow. Model can be used to support groundwater management activities.	http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html Prudic et al. 2004, Wilson and Naff 2004
PRZM	Hydrogeological	Pesticide leaching into the soil and root zone of plants (FIFRA). Estimates pesticide and nitrogen fate in the crop zone root and can simulate soil temperature, volatilization and vapor phase transport in soil, irrigation, and microbial transformation.	http://www.epa.gov/ceampubl/products.htm EPA 2005b
BIOPLUME	Two-dimensional finite difference and Method of Characteristics (MOC) model	Simulates organic contaminants in groundwater due to natural processes of dispersion, advection, sorption, and biodegradation. Simulates aerobic and anaerobic biodegradation reactions.	http://www.epa.gov/ada/csmos/models.html EPA 1998

Surface Water Quality Models

Surface water quality models are often related to, or are variations of, hydrological models. The latter are designed to predict flows in water bodies and runoff from precipitation, both of which govern the transport of aqueous contaminants. Of particular interest in some water quality models is the mixing of contaminants as a function of time and space, for example, following a point-source discharge into a river. Other features of these models are the biological, chemical, and physical removal mechanisms of contaminants, such as degradation, oxidation, and deposition, as well as the distribution of the contaminants between the aqueous phase and organisms.

Model	Type	Use	Additional Information
HSPF	Combined watershed hydrology and water quality	Total maximum daily load determinations TMDL (CWA). Watershed model simulating nonpoint pollutant load and runoff, fate and transport processes in streams.	http://www.epa.gov/ceampubl/swater/hspf/
WASP	Compartment modeling for aquatic systems	Supports management decisions by predicting water quality responses to pollutants in aquatic systems. Multicompartment model that examines both the water column and underlying benthos.	http://www.epa.gov/athens/wwqtsc/html/wasp.html Brown 1986, Brown and Barnwell 1987
QUAL2E	Steady-state and quasi-dynamic water quality model	Stream water quality model used as a planning tool for developing TMDLs. The model can simulate nutrient cycles, benthic and carbonaceous demand, algal production, among other parameters.	http://www3.bae.ncsu.edu/ Regional-Bulletins/Modeling-Bulletin/qual2e.html

			Brown 1986, Brown and Barnwell 1987

Air Quality Models

The fate of gaseous and solid particle pollutants in the atmosphere is a function of meteorology, temperature, relative humidity, other pollutants, and sunlight intensity, among other things. Models that simulate concentrations in air have one of three general designs: plume models, grid models, and receptor models. Plume models are used widely for permitting under requirements to assess the impacts of large new or modified emissions sources on air quality or to assess air toxics (HAPs) concentrations close to sources. Plume models focus on atmosphere dynamics. Grid models are used primarily to assess concentrations of secondary criteria pollutants (e.g., ozone) in regional airsheds to develop plans (SIPs) and rules with the objective of attaining ambient air quality standards (NAAQS). Both atmospheric dynamics and chemistry are important components of 3-D grid models. In contrast to mechanistic plume and grid models, receptor models are statistical; they determine the statistical contribution of various sources to pollutant concentrations at a given location based on the relative amounts of pollutants at source and receptor. Most air quality models are deterministic.

Model	Type	Use	Additional Information
CMAQ	3-D Grid	SIP development, NAAQS setting (CAA). The model provides estimates of ozone, particulates, toxics, and acid deposition and simulates chemical and physical properties related to atmospheric trace gas transformations and distributions. Model has three components including, meteorological system, an emissions model for estimating anthropogenic and natural emissions, and a chemistry-transport modeling system.	http://www.epa.gov/asmdnerl/CMAQ/index.html Byun and Ching 1999
UAM	3-D Grid	Model calculates concentrations of inert and chemically reactive pollutants and is used to evaluate air quality, particularly related to ambient ozone concentrations.	Systems Applications International, Inc., 1999
REMSAD	3-D Grid	Using simulation of physical and chemical processes in the atmosphere that impact pollutant concentrations, model calculates concentration of inert and chemically reactive pollutants.	http://www.remsad.com ICF Consulting 2005
ICSC CALPUFF	Plume	PSD permitting; toxics exposure (CAA, TSCA). Non-steady-state air quality dispersion model that simulates long range transport of pollutants.	
CMB	Receptor	Relative contributions of sources. Receptor model used for air resource management purposes.	http://www.epa.gov/scram001/receptor_cmb.htm Coulter 2004

EXPOSURE MODELS

The primary objective of exposure models is to estimate the dose of pollutant which humans or animals are exposed to via inhalation, ingestion and/or dermal uptake. These models bridge the gap between concentrations of pollutants in the environment and the doses humans receive based on their activity. Pharmacokinetic models take this one step further and estimate dose to tissues in the body. Since exposure is inherently tied to behavior, exposure models may also simulate activity, for example a model that estimates dietary consumption of pollutants. In addition to the Lifeline model described below, other examples of models that estimate dietary exposure to pesticides include Calendex and CARES. These models can be either deterministic or probabilistic, but are well-suited for probabilistic methods due to the variability of activity within a population.

Model	Type	Use	Additional Information
Lifeline	Diet, water and dermal of single chemical	Aggregate dose of pesticide via multiple pathways	http://www.thelifeline group.org Lifeline Group, Inc. 2006
IEUBK	Multipathway, single chemical	Dose of lead to children's blood via multiple pathways. Estimates exposure from lead in media (air, water, soil, dust, diet, and paint and other sources) using pharmacokinetic models to predict blood lead levels in children 6 months to 7 years old. The model can be used as a tool for the determination of site-specific cleanup levels.	http://www.epa.gov/ superfund/programs/ lead/products.htm EPA 1994
Air Pollutants Exposure Model (APEX)	Inhalation exposure model	Simulates an individual's exposure to an air pollutant and their movement through space and time in indoor or outdoor environments. Provides dose estimates and summary exposure information for each individual.	http://www.epa.gov/ttn/ fera/human_apex.html Richmond et al. 2001

HUMAN HEALTH AND ENVIRONMENT RESPONSE MODELS

Human Health Effects Models

Health effects models provide a statistical relationship between a dose of a chemical and an adverse human health effect. Health effects models are statistical methods, hence models in this category are almost exclusively empirical. They can be further classified as toxicological and epidemiological. The former refer to models derived from observations in controlled experiments, usually with nonhuman subjects. The latter refer to models derived from observations over large populations. Health models use statistical methods and assumptions that ultimately assume cause and effect. Included in this category are models that extrapolate information from non-human subject experiments. Also, physiologically based pharmacokinetic models can help predict human toxicity to contaminants through mathematical modeling of absorption, distribution, storage, metabolism, and excretion of toxicants. The output from health models is almost always a dose, such as a safe level (for example, reference dose [RfD]), a cancer potency index (CPI), or an expected health end point (for example, lethal dose for 50% of the population (LD50) or number of asthma cases). There also exist model *applications* that facilitate the use of the statistical methods.

Model	Type	Use	Additional Information
Benchmark dose model	Software tool for applying a variety of statistical models to analyze dose-response data	To estimate risk of pollutant exposure. Models fit to dose-response data to determine a benchmark dose that is associated with a particular benchmark response.	http://cfpub.epa.gov/ ncea/cfm/recordisplay. cfm?deid=20167
Linear Cancer model	Statistical analysis method	To estimate the risk posed by carcinogenic pollutants	EPA 2000

Ecological Effects Models

Ecological effects models, like human health effects models, define relationships between a level of pollutant exposure and a particular ecological indicator. Many ecological effects models simulate aquatic environments, and ecological indicators are related directly to environmental concentrations. Examples of ecological effects indicators that have been modeled are: algae blooms, BOD, fish populations, crop yields, coast line erosion, lake acidity, and soil salinity.

Model	Type	Use	Additional Information
AQUATOX	Integrated fate and effects of pollutants in aquatic environment	Ecosystem model that predicts the environmental fate of chemicals in aquatic ecosystems, as well as direct and indirect effects on the resident organisms. Potential applications to management decisions include water quality criteria and standards, TMDLs, and ecological risk assessments of aquatic systems.	http://www.epa.gov/ waterscience/models/ aquatox/ Hawkins 2005, Rashleigh 2007
BASS	Simulates fish populations exposed to pollutants (mechanistic	Models dynamic chemical bioconcentration of organic pollutants and metals in fish. Estimates are being used for ecological risks to fish in addition to realistic dietary exposures to humans and wildlife.	http://www.epa.gov/ athens/research/ modeling/bass.html
SERAFM	Steady-state modeling system used to predict mercury concentration in wildlife	Predicts total mercury concentrations in fish and speciated mercury concentrations in water and sediments.	http://www.epa.gov/ ceampubl/swater/ serafm/index.htm Knightes 2005
PATCH	Movement of invertebrates in their habitat	Provides population estimates of territorial terrestrial vertebrate species over time, in addition to survival and fecundity rates, and orientation of breeding sites. Determine ecological effects of regulation.	http://www.epa.gov/ wed/pages/models/ patch/patchmain.htm Lawler et al. 2006

ECONOMIC IMPACT MODELS

This category includes a broad group of models that are used in many different aspects of EPA's activities including: rulemaking (regulatory impact assessments), priority setting, enforcement, and retrospective analyses. Models that produce a dollar value as output belong in this category. Models can be divided into cost models, which may include or exclude behavior responses, and benefit models. The former incorporate economic theory on how markets (supply, demand, and pricing) will respond as a result of an action. Economic models are traditionally deterministic, though there is a trend toward greater use of uncertainty methods in cost-benefit analysis.

Model	Type	Use	Additional Information
ABEL	Micro Economic	Assess a single firm's ability to pay compliance costs or fees. Estimates claims from defendants that they cannot afford to pay for compliance, clean-up or civil penalties using information from tax return data and cash-flow analysis. Used for settlement negotiations.	http://iaspub.epa.gov/ edr/edr_proc_qry. navigate?P_LIST_ OPTION_CD=CSDIS& P_REG_AUTH_ IDENTIFIER=1&P_ DATA_IDENTIFIER= 90389&P_VERSION=1
Nonroad Diesel Economic Impact Model (NDEIM)	Macro economic for impact of the nonroad diesel emissions standards rule	Multimarket model to analyze how producers and consumers are expected to respond to compliance costs associated with the rule. Estimates and stratifies emissions for nonroad equipment. Model can be used to inform State Implementation Plans and regulatory analyses.	http://www.epa.gov/ttn/ atw/nsps/cinsps/ ci_nsps_eia_reportfinal forproposal.pdf
BenMAP	Noneconomic and economic benefits from air quality	Model that estimates the health benefits associated with air quality changes by estimating changes in incidences of a wide range of health outcomes and then placing an economic value on these reduced incidences.	http://www.epa.gov/ttne cas1/benmodels.html

NONECONOMIC IMPACT MODELS

Noneconomic impact models evaluate the effects of contaminants on a variety of noneconomic parameters, such as on crop yields and buildings. Note that other noneconomic impacts, such as impacts on human health or ecosystems, are derived from the human health and ecological effects models discussed previously.

Model	Type	Use	Additional Information
TDM (Travel Demand Management)	Model used to evaluate travel demand management strategies	Evaluates travel demand management strategies to determine vehicle-trip reduction effects. Model used to support transit policies including HOV lanes, carpooling, telecommuting, and pricing and travel subsidies.	http://www.fhwa.dot.gov/environment/cmaqeat/descriptions_tdm_evaluation_model.htm
CERES-Wheat	Crop-growth yield model	Simulates effects of planting density, weather, water, soil, and nitrogen on crop growth, development, and yield. Predicts management strategies that impact crop yield.	http://nowlin.css.msu.edu/wheat_book/
PHREEQE-A	Models effects of acidification on stone	Simulates the effects of acidic solutions on carbonate stone.	Parkhurst et al. 1990

Appendix C: Supplementary Material on Quality Assurance Planning and Protocols

This section consists of a series of text boxes meant to supplement concepts and references made in the main body of the document. They are not meant as a comprehensive discussion on QA practices, and each box should be considered as a discrete unit. Individually, the text boxes provide additional background material for specific sections of the main document. The complete QA manuals for each subject area discussed in this guidance and referred to below should be consulted for more complete information on QA planning and protocols.

Box C1: Background on EPA Quality System

The EPA Quality System defined in EPA Order 5360.1 A2, “Policy and Program Requirements for the Mandatory Agency-Wide Quality System” (EPA 2000e), covers environmental data produced from models as well as “any measurement or information that environmental processes, location, or conditions; ecological or health effects and consequences; or the performance of environmental technology.” For EPA, environmental data include information collected directly from measurements, produced from models, and compiled from other sources such as databases and literature.

The EPA Quality System is based on an American National Standard, ANSI 1994. Consistent with minimum specifications of this standard, §6.a.(7) of EPA Order 5360.1 A2 states that EPA organizations will develop a Quality System that includes “approved” Quality Assurance (QA) Project Plans, or equivalent documents defined by the Quality Management Plan, for all applicable projects and tasks involving environmental data with review and approval having been made by the EPA QA Manager (or authorized representative defined in the Quality Management Plan). The approval of the QA Project Plan containing the specifications for the product(s) and the checks against those specifications (assessments) for implementation is an important management control assuring records to avoid fiduciary “waste and abuse” (Federal Managers’ Financial Integrity Act of 1982[9] with annual declarations including conformance to the EPA Quality System). The assessments (including peer review) support the product acceptance for models and their outputs and approval for use such as supporting environmental management decisions by answering questions, characterizing environmental processes or conditions, and direct decision support such as economic analyses (process planned in Group D in the Guidance for QA Project Plans for Modeling). EPA’s policies for QA Project Plans are provided in Chapter 5 of EPA’s Manual 5360 A1 (EPA 2000e), the *EPA Quality Manual for Environmental Programs* (EPA 2000f) for in-house modeling, and Requirements for Quality Assurance Project Plans (QA/G5-M) (EPA 2002b) for modeling done through extramural agreements (e.g., contracts 48 CFR 46, grants and cooperative agreements 40 CFR 30, 31, and 35). QA requirements must be negotiated and written into Interagency Agreements if the project is funded by EPA; if funds are received by EPA, EPA Manual 5360 A1 (EPA 2000e) applies.

EPA Order 5360.1 A2 also states that EPA organizations’ Quality Systems must include “use of a systematic planning approach to develop acceptance or performance criteria for all work covered” and “assessment of existing data, when used to support Agency decisions or other secondary purposes, to verify that they are of sufficient quantity and adequate quality for their intended use.”

[9] Federal Managers Financial Integrity Act of 1982, P.L. 97-255—(H.R. 1526), September 8, 1982.

Box C2: Configuration Tests Specified in the QA Program

During code verification, the final set of computer code is scrutinized to ensure that the equations are programmed correctly and that sources of error, such as rounding, are minimal. This process is likely to be more extensive for new computer code. For existing code, the criteria used for previous verification, if known, can be described or cited. Any additional criteria specific to the modeling project can be specified, along with how the criteria were established. Possible departures from the criteria are discussed, along with how the departures can affect the modeling process.

Software code development inspections: An independent person or group other than the author(s) examines software requirements, software design, or code to detect faults, programming errors, violations of development standards, or other problems. All errors found are recorded at the time of inspection, with later verification that all errors found have been successfully corrected.

Software code performance testing: Software used to compute model predictions is tested to assess its performance relative to specific response times, computer processing usage, run time, convergence to solutions, stability of the solution algorithms, absence of terminal failures, and other quantitative aspects of computer operation.

Testing of model modules: Checks ensure that the computer code for each module is computing outputs accurately and within any specific time constraints. (Modules are different segments or portions of the model linked together to obtain the final model prediction.)

Model framework testing: The full model framework is tested as the ultimate level of integration testing to verify that all project-specific requirements have been implemented as intended.

Integration testing: The computational and transfer interfaces between modules need to allow an accurate transfer of information from one module to the next, and ensure that uncertainties in one module are not lost or changed when that information is transferred to the next module. These tests detect unanticipated interactions between modules and track down their cause(s). (Integration tests should be designed and applied hierarchically by increasing, as testing proceeds, the number of modules tested and the subsystem complexity.)

Regression testing: All testing performed on the original version of the module or linked modules is repeated to detect new "bugs" introduced by changes made in the code to correct a model.

Stress testing (of complex models): This ensures that the maximum load (e.g., real-time data acquisition and control systems) does not exceed limits. The stress test should attempt to simulate the maximum input, output, and computational load expected during peak usage. The load can be defined quantitatively using criteria such as the frequency of inputs and outputs or the number of computations or disk accesses per unit of time.

Acceptance testing: Certain contractually required testing may be needed before the new model or the client accepts model application. Specific procedures and the criteria for passing the acceptance test are listed before the testing is conducted. A stress test and a thorough evaluation of the user interface is a recommended part of the acceptance test.

Beta testing of the pre-release hardware/software: Persons outside the project group use the software as they would in normal operation and record any anomalies they encounter or answer questions provided in a testing protocol by the regulatory program. The users report these observations to the regulatory program or specified developers, who address them before release of the final version.

Reasonableness checks: These checks involve items like order-of-magnitude, unit, and other checks to ensure that the numbers are in the range of what is expected.

Note: This section is adapted from (EPA 2002b).

Box C3: Quality Assurance Planning Suggestions for Model Calibration Activities

Information related to objectives and acceptance criteria for calibration activities that generally appear at the beginning of this QA Project Plan element includes the following:

Objectives of model calibration: This includes expected accomplishments of the calibration and how the predictive quality of the model might be improved as a result of implementing the calibration procedures.

Acceptance criteria: The specific limits, standards, goodness-of-fit, or other criteria on which a model will be judged as being properly calibrated (e.g., the percentage difference between reference data values from the field or laboratory and predicted results from the model). This includes a mention of the types of data and other information that will be necessary to acquire in order to determine that the model is properly calibrated (e.g., field data, laboratory data, predictions from other accepted models). In addition to addressing these questions when establishing acceptance criteria, the QA Project Plan can document the likely consequences (e.g., incorrect decision making) of selecting data that do not satisfy one or more of these areas (e.g., are non-representative, are inaccurate), as well as procedures in place to minimize the likelihood of selecting such data.

Justifying the calibration approach and acceptance criteria: Each time a model is calibrated, it is potentially altered. Therefore, it is important that the different calibrations, the approaches taken (e.g., qualitative versus quantitative), and their acceptance criteria are properly justified. This justification can refer to the overall quality of the standards being used as a reference or to the quality of the input data (e.g., whether data are sufficient for statistical tests to achieve desired levels of accuracy).

Box C4: Definition of Quality

notions of integrity, utility, and objectivity. Integrity refers to the protection of information from unauthorized access or revision to ensure that it is not compromised through corruption or falsification. In the context of environmental models, integrity is often most relevant to protection of code from unauthorized or inappropriate manipulation (see Box 2). Utility refers to the usefulness of the information to the intended users. The utility of modeling projects is aided by the implementation of a systematic planning approach that includes the development of acceptance or performance criteria (see Box 1). Objectivity involves two distinct elements, presentation and substance. Objectivity includes whether disseminated information is being presented in an accurate, clear, complete and unbiased manner. It also involves a focus on ascertaining accurate, reliable, and unbiased information.

EPA's five general assessment factors (EPA 2003b) for evaluating the quality and relevance of scientific and technical information supporting Agency actions are: soundness, applicability and utility, clarity and completeness, uncertainty and variability, and evaluation and review. Soundness refers to the extent to which a model is appropriate for its intended application and is a reasonable representation of reality. Applicability and utility describe the extent to which the information is relevant and appropriate for the Agency's intended use. Clarity and completeness refer to documentation of the data, assumptions, methods, quality controls, and analysis employed to generate the model outputs. Uncertainty and variability highlight the extent to which limitations in knowledge and information and natural randomness in input data and models are evaluated and characterized. Evaluation and review evaluate the extent of independent application, replication, evaluation, validation, and peer review of the information or of the procedures, measures, methods, or models employed to generate the information.

Appendix D: Best Practices for Model Evaluation

D.1 Introduction

This appendix presents a practical guide to the best practices for model evaluation (please see Section 4.1 for descriptions of these practices). These best practices are:

- Scientific peer review (Section 4.1.1)
- Quality assurance project planning (Section 4.1.2)
- Corroboration (Section 4.1.3)
- Sensitivity analysis (Section 4.1.3)
- Uncertainty analysis (Section 4.1.3)

The objective of model evaluation is to determine whether a model is of sufficient quality to inform a regulatory decision. For each of these best practices, this appendix provides a conceptual overview for model evaluation and introduces a suite of “tools” that can be used in partial fulfillment of the best practice. The appropriate use of these tools is discussed and citations to primary references are provided. Users are encouraged to obtain more complete information about tools of interest, including their theoretical basis, details of their computational methods, and the availability of software.

Figure D.1.1 provides an overview of the steps in the modeling process that are discussed in this guidance. Items in bold in the figure, including peer review, model corroboration, uncertainty analysis, and sensitivity analysis, are discussed in this section on model evaluation.

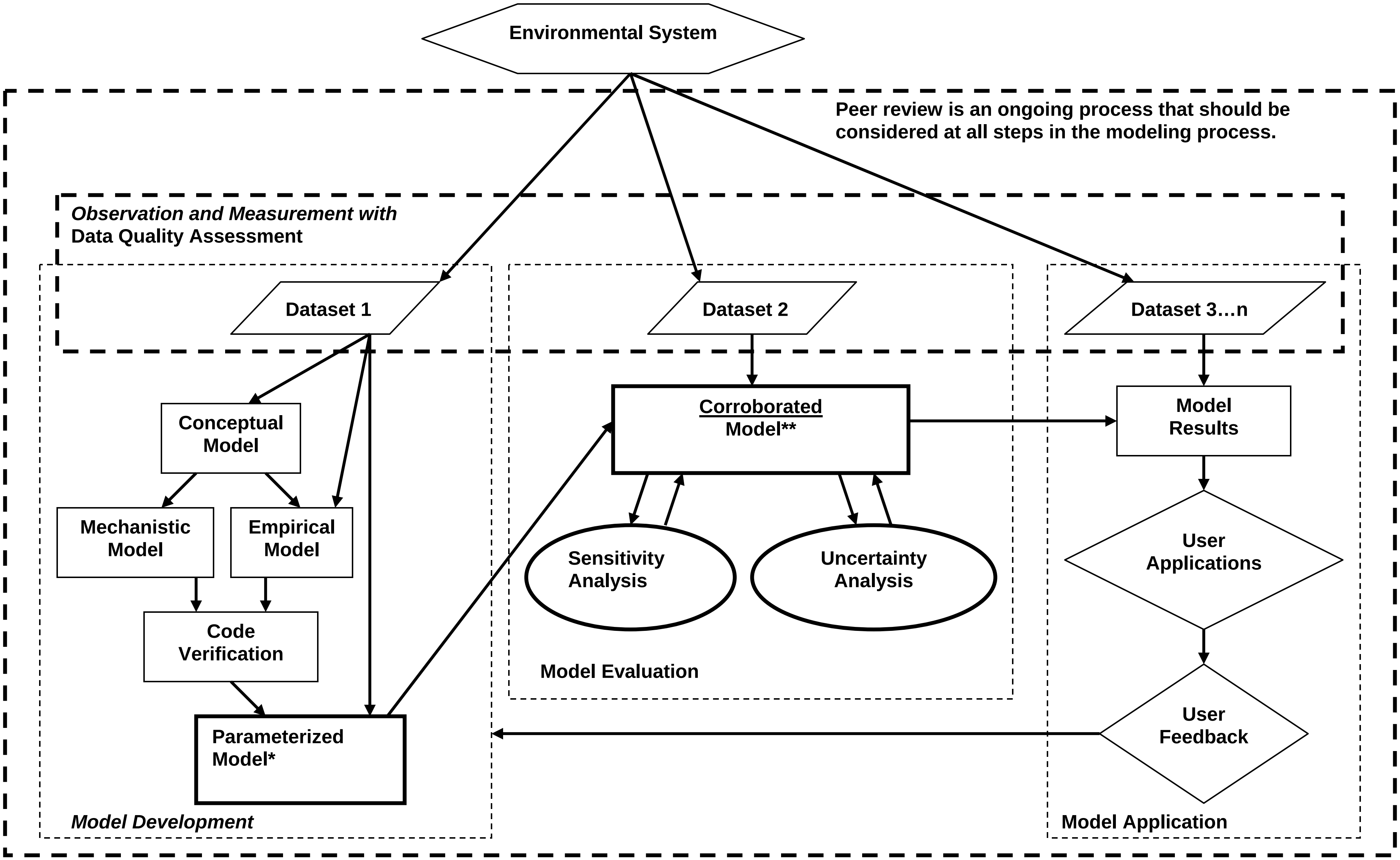


Figure D.1.1. The modeling process.
* In some disciplines parameterization may include, or be referred to as, calibration.
** Qualitative and/or quantitative corroboration should be performed when necessary.

D.2 Scientific Peer Review

EPA policy states that major science-based and technical products related to Agency decisions should normally be peer-reviewed. Agency managers determine and are accountable for the decision whether to employ peer review in particular instances and, if so, its character, scope, and timing. EPA has published guidance for program managers responsible for implementing the peer review process for models (Beck et al. 1994). This guidance discusses peer review mechanisms, the relationship of external peer review to the process of environmental regulatory model development and application, documentation of the peer review process, and specific elements of what could be covered in an external peer review of model development and application.

The general process for external peer review of models is as follows (Beck et al. 1994, Press 1992):

- Step 0: The program manager within the originating office (AA-ship or Region) identifies elements of the regulatory process that would benefit from the use of environmental models. A review/solicitation of currently available models and related research should be conducted. If it is concluded that the development of a new model is necessary, a research/development work plan is prepared.
- Step 0b (optional): The program manager may consider internal and/or external peer review of the research/development concepts to determine whether they are of sufficient merit and whether the model is likely to achieve the stated purpose.
- Step 1: The originating office develops a new or revised model or evaluates the possible novel application of a model developed for a different purpose.
- Step 1b (optional): The program manager may consider internal and/or external peer review of the technical or theoretical basis prior to final development, revision, or application at this stage. For model development, this review should evaluate the stated application niche.
- Step 2: Initial Agency-wide (internal) peer review/consultation of model development and/or proposed application may be undertaken by the developing originating office. Model design, default parameters, etc., and/or intended application are revised (if necessary) based on consideration of internal peer review comments.
- Step 3: The origination office considers external peer review. Model design, default parameters, etc., and/or intended application are revised (if necessary) based on consideration of internal peer review comments.
- Step 4: Final Agency-wide evaluation/consultation may be implemented by the originating office. This step should consist of consideration of external peer review comments and documentation of the Agency's response to scientific/technical issues.

(Note: Steps 2 and 4 are relevant when there is either an internal Agency standing or an ad hoc peer review committee or process).

Box D1: Elements of External Peer Review for Environmental Regulatory Models (Box 2-4 from NRC's *Models in Environmental Regulatory Decision Making*)

Model Purpose/Objectives

- What is the regulatory context in which the model will be used and what broad scientific question is the model intended to answer?
- What is the model's application niche?
- What are the model's strengths and weaknesses?

Major Defining and Limiting Considerations

- Which processes are characterized by the model?
- What are the important temporal and spatial scales?
- What is the level of aggregation?

Theoretical Basis for the Model — formulating the basis for problem solution

- What algorithms are used within the model and how were they derived?
- What is the method of solution?
- What are the shortcomings of the modeling approach?

Parameter Estimation

- What methods and data were used for parameter estimation?
- What methods were used to estimate parameters for which there were no data?
- What are the boundary conditions and are they appropriate?

Data Quality/Quantity

Questions related to model design include:

- What data were utilized in the design of the model?
- How can the adequacy of the data be defined taking into account the regulatory objectives of the model?

Questions related to model application include:

- To what extent are these data available and what are the key data gaps?
- Do additional data need to be collected and for what purpose?

Key Assumptions

- What are the key assumptions?
- What is the basis for each key assumption and what is the range of possible alternatives?
- How sensitive is the model toward modifying key assumptions?

Model Performance Measures

- What criteria have been used to assess model performance?
- Did the data bases used in the performance evaluation provide an adequate test of the model?
- How does the model perform relative to other models in this application niche?

Model Documentation and Users Guide

- Does the documentation cover model applicability and limitations, data input, and interpretation of results?

Retrospective

- Does the model satisfy its intended scientific and regulatory objectives?
- How robust are the model predictions?
- How well does the model output quantify the overall uncertainty?

Source: EPA 1994b.

D.3 Quality Assurance Project Planning

Box D2: Quality Assurance Planning and Data Acceptance Criteria

The QA Project Plan needs to address four issues regarding information on how non-direct measurements are acquired and used on the project (EPA 2002d):

- The need and intended use of each type of data or information to be acquired.
- How the data will be identified or acquired, and expected sources of these data.
- The method of determining the underlying quality of the data.
- The criteria established for determining whether the level of quality for a given set of data is acceptable for use on the project.

Acceptance criteria for individual data values generally address issues such as the following:

Representativeness: Were the data collected from a population sufficiently similar to the population of interest and the model-specified population boundaries? Were the sampling and analytical methods used to generate the collected data acceptable to this project? How will potentially confounding effects in the data (e.g., season, time of day, location, and scale incompatibilities) be addressed so that these effects do not unduly impact the model output?

Bias: Would any characteristics of the dataset directly impact the model output (e.g., unduly high or low process rates)? For example, has bias in analysis results been documented? Is there sufficient information to estimate and correct bias? If using data to develop probabilistic distributions, are there adequate data in the upper and lower extremes of the tails to allow for unbiased probabilistic estimates?

Precision: How is the spread in the results estimated? Is the estimate of variability sufficiently small to meet the uncertainty objectives of the modeling project as stated in Element A7 (Quality Objectives and Criteria for Model Inputs/Outputs) (e.g., adequate to provide a frequency of distribution)?

Qualifiers: Have the data been evaluated in a manner that permits logical decisions on the data's applicability to the current project? Is the system of qualifying or flagging data adequately documented to allow data from different sources to be used on the same project (e.g., distinguish actual measurements from estimated values, note differences in detection limits)?

Summarization: Is the data summarization process clear and sufficiently consistent with the goals of this project (e.g., distinguish averages or statistically transformed values from unaltered measurement values)? Ideally, processing and transformation equations will be made available so that their underlying assumptions can be evaluated against the objectives of the current project.

D.4 Corroboration

In this guidance, "corroboration" is defined as all quantitative and qualitative methods for evaluating the degree to which a model corresponds to reality. In practical terms, it is the process of "confronting models with data" (Hilborn and Mangel 1997). In some disciplines, this process has been referred to as validation. In general, the term "corroboration" is preferred because it implies a claim of usefulness and not truth.

Corroboration is used to understand how consistent the model is with data. However, uncertainty and variability affect how accurately both models and data represent reality because both models and data (observations) are approximations of some system. Thus, to conduct corroboration meaningfully (i.e., as a tool to assess how well a model represents the system being modeled), this process should begin by characterizing the uncertainty and variability in the corroboration data. As discussed in Section 4.1.3.1, variability stems from the natural randomness or stochasticity of natural systems and can be better captured or characterized in a model but not reduced. In contrast, uncertainty can be minimized with improvements in model structure (framework), improved measurement and analytical techniques, and more comprehensive data for the system being studied. Hence, even a "perfect" model (that contains no measurement error and predicts the correct ensemble average) may deviate from observed field measurements at a given time.

Depending on the type (qualitative and/or quantitative) and availability of data, corroboration can involve hypothesis testing and/or estimates of the likelihood of different model outcomes.

D.4.1 Qualitative Corroboration

Qualitative model corroboration involves expert judgment and tests of intuitive behavior. This type of corroboration uses “knowledge” of the behavior of the system in question, but is not formalized or statistics-based. Expert knowledge can establish model reliability through *consensus* and *consistency*. For example, an expert panel consisting of model developers and stakeholders could be convened to determine whether there is agreement that the methods and outputs of a model are consistent with processes, standards, and results used in other models. Expert judgment can also establish model credibility by determining if model-predicted behavior of a system agrees with best-available understanding of internal processes and functions.

D.4.2 Quantitative Methods

When data are available, model corroboration may involve comparing model predictions to independent empirical observations to investigate how well a model's description of the world fits the observational data. This involves using both statistical measures for goodness of fit and numerical procedures to facilitate these calculations. The can be done graphically or by calculating various statistical measures of fit of a model’s results to data.

Recall that a model’s *application niche* is the set of conditions under which the use of a model is scientifically defensible (Section 5.2.3); it is the domain of a model’s intended applicability. If the model being evaluated purports to estimate an average value across the entire system, then one method to deal with corroboration data is to stratify model results and observed data into “regimes,” subsets of data within which system processes operate similarly. Corroboration is then performed by comparing the average of model estimates and observed data within each regime (ASTM 2000).

D.4.2.1 Graphical Methods

Graphical methods can be used to compare the *distribution* of model outputs to independent observations. The degree to which these two distributions overlap, and their respective shapes, provide an indication of model performance with respect to the data. Alternately, the differences between observed and predicted data pairs can be plotted and the resulting probability density function (PDF) used to indicate precisions and bias. Graphical methods for model corroboration can be used to indicate bias, skewness, and kurtosis of model results. Skewness indicates the relative precision of model results, while bias is a reflection of accuracy. Kurtosis refers to the amplitude of the PDF.

D.4.2.2 Deviance Measures

Methods for calculating model bias:

Mean error calculates the average deviation between models and data (e = model-data) by dividing the sum of errors (Σe) by total number of data points compared (m).

$$MeanError = \frac{\Sigma e}{m} \quad \text{(in original measurement units)}$$

Similarly, **mean % error** provides a unit-less measure of model bias:

$$MeanError(\%) = \frac{\Sigma e / s}{m} * 100 ,$$

where "s" is the sample or observational data in original units.

Methods for calculating bias and precision:
Mean square error (MSE):

$$MSE = \frac{\Sigma e^2}{m}$$

(Large deviations in any single data pair (model-data) can dominate this metric.)

Mean absolute error:

$$MeanAbsError = \frac{\Sigma |e|}{m}$$

<u>D.4.2.3 Statistical Tests</u>
A more formal hypothesis testing procedure can also be used for model corroboration. In such cases, a test is performed to determine if the model outputs are statistically significantly different from the empirical data. Important considerations in these tests are the probability of making type I and type II errors and the shape of the data distributions, as most of these metrics assume the data are distributed normally. The test-statistic used should also be based on the number of data-pairs (observed and predicted) available.

There are a number of comprehensive texts that may help analysts determine the appropriate statistical and numerical procedures for conducting model corroboration. These include:

- Efron, B., and R. Tibshirani. 1993. *An Introduction to the Bootstrap*. New York: Chapman and Hall.
- Gelman, A.J.B., H.S. Carlin, and D.B. Rubin. 1995. *Bayesian Data Analysis*. New York: Chapman and Hall.
- McCullagh, P., and J.A. Nelder. 1989. *Generalized Linear Models*. New York: Chapman and Hall.
- Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. 1986. *Numerical Recipes*. Cambridge, UK: Cambridge University Press.
- Snedecor, G.W., and W.G. Cochran. 1989. *Statistical Methods*. Eighth Ed. Iowa State University Press.

D.4.3 Evaluating Multiple Models

> *Models are metaphorical (albeit sometimes accurate) descriptions of nature, and there can never be a "correct" model. There may be a "best" model, which is more consistent with the data than any of its competitors, or several models may be contenders because each is consistent in some way with the data and none clearly dominates the others. It is the job of the ecological detective to determine the support that the data offer for each competing model or hypothesis.*
> — Hillborn and Mangel 1997, *Ecological Detective*

In the simplest sense, a first cut of model performance is obtained by examining which model minimizes the sum of squares (SSq) between observed and model-predicted data.

$$SSq = \sum (pred - obs)^2$$

The SSq is equal to the squared differences between model-predicted values and observational values. If data are used to fit models and estimate parameters, the fit will automatically improve with each higher-order model — e.g., simple linear model, $y = a + bX$, vs. a polynomial model, $y = a + bX + cX^2$.

It is therefore useful to apply a penalty for additional parameters to determine if the improvement in model performance (minimizing SSq deviation) justifies an increase in model complexity. The question is essential whether the decrease in the sum of squares is statistically significant.

The SSq is best applied when comparing several models using a single dataset. However, if several datasets are available the Normalized Mean Square Error (NMSE) is typically a better statistic, as it is normalized to the product of the means of the observed and predicted values (see discussion and references, Section D.4.4.4).

D.4.4 An Example Protocol for Selecting a Set of Best Performing Models

During the development phase of an air quality dispersion model and in subsequent upgrades, model performance is constantly evaluated. These evaluations generally compare simulation results using simple methods that do not account for the fact that models only predict a portion of the variability seen in the observations. To fill a part of this void, the U.S. Environmental Protection Agency (EPA) developed a standard that has been adopted by the ASTM International, designation D 6589–00 for Statistical Evaluation of Atmospheric Dispersion Model Performance (ASTM 2000). The following discussion summarizes some of the issues discussed in D 6589.

D.4.4.1 Define Evaluation Objectives

Performing a statistical model evaluation involves defining those evaluation objectives (features or characteristics) within the pattern of observed and modeled concentration values that are of interest to compare. As yet, no one feature or characteristic has been found that can be defined within a concentration pattern that will fully test a model's performance. For instance, the maximum surface concentration may appear unbiased through a compensation of errors in estimating the lateral extent of the dispersing material and in estimating the vertical extent of the dispersing material. Adding into consideration that other biases may exist (e.g., in treatment of the chemical and removal processes during transport, in estimating buoyant plume rise, in accounting for wind direction changes with height, in accounting for penetration of material into layers above the current mixing depth, in systematic variation in all of these biases as a function of atmospheric stability), one can appreciate that there are many ways that a model can falsely give the appearance of good performance.

In principle, modeling diffusion involves characterizing the size and shape of the volume into which the material is dispersing as well as the distribution of the material within this volume. Volumes have three dimensions, so a model evaluation will be more complete if it tests the model's ability to characterize diffusion along more than one of these dimensions.

D.4.4.2 Define Evaluation Procedures

Having selected evaluation objectives for comparison, the next step is to establish an evaluation procedure (or series of procedures), which defines how each evaluation objective will be derived from the available information. Development of statistical model evaluation procedures begins with technical definitions of the terminology used in the goal statement. In the following discussion, we use a plume dispersion model example, but the thought process is valid as well for regional photochemical grid models.

Suppose the evaluation goal is to test models' ability to replicate the average centerline concentration as a function of transport downwind and as a function of atmospheric stability. Several questions must be answered to achieve this goal: What is an "average centerline concentration"? What is "transport downwind"? How will "stability" be defined?

What questions arise in defining the average centerline concentration? Given a sampling arc of concentration values, it is necessary to decide whether the centerline concentration is the maximum value seen anywhere along the arc or that seen near the center of mass of the observed lateral concentration distribution. If one chooses the latter concept, one needs a definition of how "near" the center of mass one has to be, to be representative of a centerline concentration value. One might decide to select all values within a specific range (nearness to the center of mass). In such a case, either a definition or a procedure will be needed to define how this specific range will be determined. A decision will have to be made on the treatment of observed zero (and near measurement threshold) concentrations. To discard such values is to say that low concentrations cannot occur near a plume's center of mass, which is a dubious assumption. One might test to see if conclusions reached regarding the "best performing model" are sensitive to the decision made on the treatment of near-zero concentrations.

What questions arise in defining "transport downwind"? During near-calm wind conditions, when transport may have favored more than one direction over the sampling period, "downwind" is not well described by one direction. If plume models are being tested, one might exclude near-calm conditions, since plume models are not meant to provide meaningful results during such conditions. If puff models or grid models are being tested, one might sort the near-calm cases into a special regime for analysis.

What questions arise in defining "stability"? For surface releases, surface-layer Monin-Obukhov length, L, has been found to adequately define stability effects; for elevated releases, Z_i/L, where Z_i is the mixing depth, has been found to be a useful parameter for describing stability effects. Each model likely has its own meteorological processor. It is likely that different processors will have different values for L and Z_i for each of the evaluation cases. There is no one best way to deal with this problem. One solution might be to sort the data into regimes using each of the models' input values, and see if the conclusions reached as to best performing model are affected.

What questions arise if one is grouping data together? If one is grouping data together for which the emission rates are different, one might choose to resolve this difference by normalizing the concentration values by dividing by the respective emission rates. To divide by the emission rate, either one has a constant emission rate over the entire release or the downwind transport is sufficiently obvious that one can compute an emission rate, based on travel time, that is appropriate for each downwind distance.

Characterizing the plume transport direction is highly uncertain, even with meteorological data collected specific for the purpose. Thus, we expect that the simulated position of the plume will not overlap the observed position of the plume. One must decide how to compare a feature (or characteristic) in a concentration pattern, when uncertainties in transport direction are large. Will the observed and modeled patterns be shifted, and if so, in what manner?

This discussion is not meant to be exhaustive, but to be illustrative of how the thought process might evolve. When terms are defined, other questions arise that — when resolved — eventually produce an analysis that will compute the evaluation objective from the available data. There likely is more than one answer to the questions that develop. This may cause different people to develop different objectives and procedures for the same goal. If the same set of models is chosen as the best-performing, regardless of which path is chosen, one can likely be assured that the conclusions reached are robust.

D.4.4.3 Define Trends in Modeling Bias

In this discussion, references to observed and modeled values refer to the observed and model evaluation objectives (e.g., regime averages). A plot of the observed and modeled values as a function of one of the model input parameters is a direct means for detecting model bias. Such comparison has been recommended and employed in a variety of investigations, e.g., Fox (1981), Weil et al. (1992), Hanna (1993) In some cases the comparison is the ratio formed by dividing the modeled value by the observed value, plotted as a function of one or more of the model input parameters. If the data have been stratified into regimes, one can also display the standard error estimates on the respective modeled and observed regime averages. If the respective averages are encompassed by the error bars (typically plus and minus two times the standard error estimates), one can assume the differences are not significant. As Hanna [11] describes, this a "seductive" inference. Procedures to provide a robust assessment of the significance of the differences are defined in ASTM D 6589 (ASTM 2000).

D.4.4.4 Summary of Performance

As an example of overall summary of performance, we will discuss a procedure constructed using the scheme introduced by Cox and Tikvart (1990) as a template. The design for statistically summarizing model performance over several regimes is envisioned as a five-step procedure.

1. Form a replicate sample using concurrent sampling of the observed and modeled values for each regime. Concurrent sampling associates results from all models with each observed value, so that selection of an observed value automatically selects the corresponding estimates by all models.
2. Compute the average of observed and modeled values for each regime.
3. Compute the normalized mean square error, NMSE, using the computed regime averages, and store the value of the NMSE computed for this pass of the bootstrap sampling.
4. Repeat steps 1 through 3 for all bootstrap sampling passes (typically of order 500).
5. Implement the procedure described in ASTM D 6589 (ASTM 2000) to detect which model has the lowest computed NMSE value (call this the "base" model) and which models have NMSE values that are significantly different from the "base" model.

In the Cox and Tikvart (1990) analysis, the data were sorted into regimes (defined in terms of Pasquill stability category and low/high wind speed classes), and bootstrap sampling was used to develop standard error estimates on the comparisons. The performance measure was the robust highest concentration (computed from the raw observed cumulative frequency distribution), which is a comparison of the highest concentration values (maxima), which most models do not contain the physics to simulate. This procedure can be improved if intensive field data are used and the performance measure is the NMSE computed from the modeled and observed regime averages of centerline concentration values as a function of stability along each downwind arc, where each regime is a particular distance downwind for a defined stability range.

The data demands are much greater for using regime averages than for using individual concentrations. Procedures that analyze groups (regimes) of data include intensive tracer field studies, with a dense receptor network, and many experiments. Whereas, Cox and Tikvart (1990) devised their analysis to make use of very sparse receptor networks having one or more years of sampling results. With dense receptor networks, attempts can be made to compare average modeled and "observed" centerline concentration values, but only a few of these experiments have sufficient data to allow stratification of the data into regimes for analysis. With sparse receptor networks, there are more data for analysis, but there is insufficient information to define the observed maxima relative to the dispersing plume's center of mass. Thus, there is uncertainty as to whether or not the observed maxima are representative of centerline concentration values. It is not obvious that the average of the *n* (say 25) observed maximum hourly concentration values (for a particular distance downwind and narrowly defined stability range) is the ensemble average centerline concentration the model is predicting. In fact, one might anticipate that the average of the *n* maximum concentration values is likely to be higher than the ensemble average of the centerline concentration. Thus the testing procedure outlined by Cox and Tikvart (1990) may favor selection of poorly formed models that routinely underestimate the lateral diffusion (and thereby overestimate the plume centerline concentration). This in turn, may bias such models' ability to characterize concentration patterns for longer averaging times.

It is therefore concluded that once a set of "best-performing models" has been selected from an evaluation using intensive field data that tests a model's ability to predict the average characteristics to be seen in the observed concentration patterns, evaluations using sparse networks are seen as useful extensions to further explore the performance of well-formulated models for other environs and purposes.

D.5 Sensitivity Analysis

This section provides a broad overview of uncertainty and sensitivity analyses and introduces various methods used to conduct the latter. A table at the end of this section summarizes these methods' primary features and citations to additional resources for computational detail.

D.5.1 Introducing Sensitivity Analyses and Uncertainty Analysis

A model approximates reality in the face of scientific uncertainties. Section 4.1.3.1 identifies and defines various sources of model uncertainty. External peer reviewers of EPA models have consistently recommended that EPA communicate this uncertainty through uncertainty analysis and sensitivity analysis, two related disciplines. Uncertainty analysis investigates the effects of lack of knowledge or potential errors of model inputs (e.g., the “uncertainty” associated with parameter values); when combined with sensitivity analysis, it allows a model user to be more informed about the confidence that can be placed in model results. Sensitivity analysis measures the effect of changes in input values or assumptions (including boundaries and model functional form) on the outputs (Morgan and Henrion 1990); it is the study of how uncertainty in a model output can be systematically apportioned to different sources of uncertainty in the model input (Beck et al. 1994). By investigating the “relative sensitivity” of model parameters, a user can become knowledgeable of the relative importance of parameters in the model.

Consider a model represented as a function f, with inputs x_1 and x_2, and with output y, such that $y = f(x_1,x_2)$. Figure D.5.1 schematically depicts how uncertainty analysis and sensitivity analysis would be conducted for this model. Uncertainty analysis would be conducted by determining how y responds to variation in inputs x_1 and x_2, the graphic depiction of which is referred to as the model’s response surface. Sensitivity analysis would be conducted by apportioning the respective contributions of x_1 and x_2 to changes in y. The schematic should *not* be construed to imply that uncertainty analysis and sensitivity analysis are sequential events. Rather, they are generally conducted by trial and error, with each type of analysis informing the other. Indeed, in practice, the distinction between these two related disciplines may be irrelevant. For purposes of clarity, the remainder of this appendix will refer exclusively to sensitivity analysis.

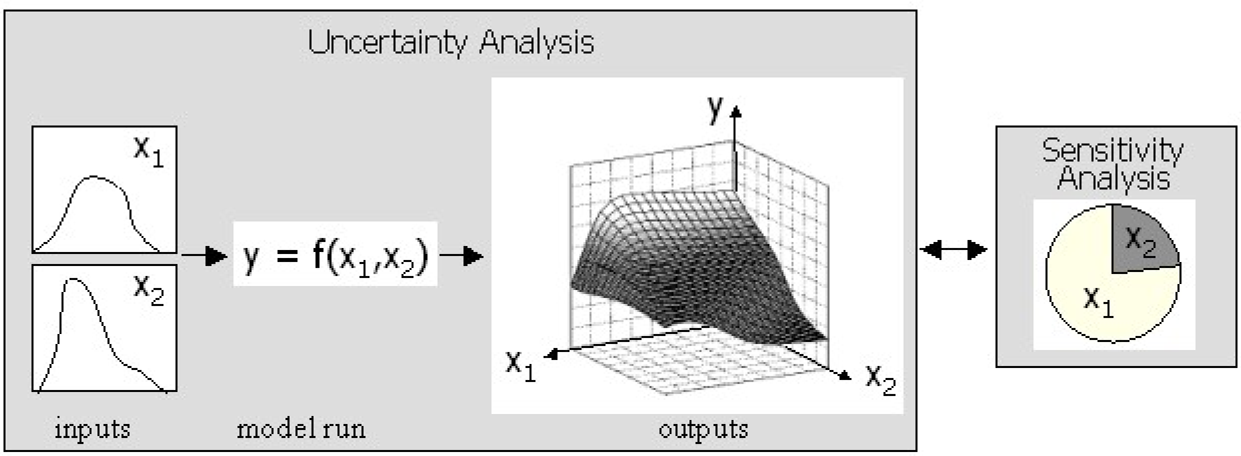


Figure D.5.1. Uncertainty and sensitivity analyses. Uncertainty analysis investigates the effects of lack of knowledge or potential errors of model inputs. Sensitivity analysis evaluates the respective contributions of inputs x_1 and x_2 to output y.

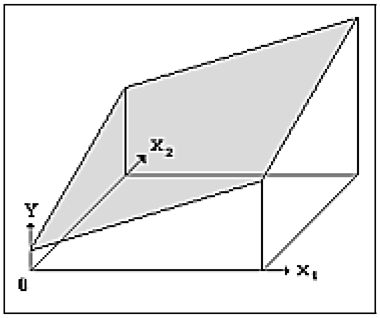
D.5.2 Sensitivity Analysis and Computational Complexity

Choosing the appropriate uncertainty analysis/sensitivity analysis method is often a matter of trading off between the amount of information one wants from the analyses and the computational difficulties of the analyses. These computational difficulties are often inversely related to the number of assumptions one is willing or able to make about the shape of a model’s response surface.

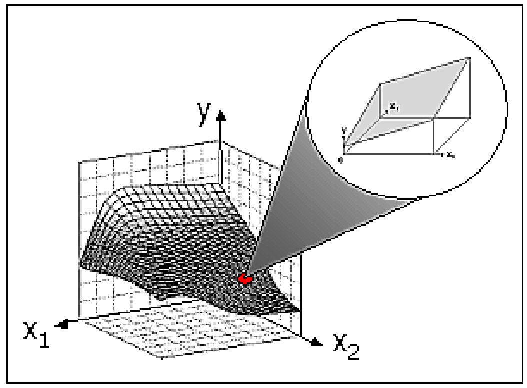
Consider once again a model represented as a function f, with inputs x_1 and x_2 and with output y, such that $y = f(x_1,x_2)$. *Sensitivity* measures how output changes with respect to an input. This is a straightforward enough procedure with differential analysis if the analyst:

- Can assume that the model's response surface is a hyperplane, as in Figure D.5.2(1);
- Accepts that the results apply only to specific points on the response surface and that these points are monotonic first order, as in Figure D.5.2 (2);[10] or
- Is unconcerned about interactions among the input variables.

Otherwise, sensitivity analysis may be more appropriately conducted using more intensive computational methods.



(1)



(2)

Figure D.5.2. It's hyperplane and simple. (1) A model response surface that is a hyperplane can simplify sensitivity analysis computations. (2) The same computations can also be used for other response surfaces, but only as approximations around a single locus.

This guidance suggests that, depending on assumptions underlying the model, the analyst should use non-intensive sensitivity analysis techniques to initially identify those inputs that generate the most sensitivity, then apply more intensive methods to this smaller subset of inputs. It may therefore be useful to categorize the various sensitivity analysis techniques into methods that (a) can be quickly used to screen for the more important input factors; (b) are based on differential analyses; (c) are based on sampling; and (d) are based on variance methods.

D.5.3 Screening Tools

<u>D.5.3.1 Tools That Require No Model Runs</u>
Cullen and Frey (1999) suggest that summary statistics measuring input uncertainty can serve as preliminary screening tools without additional model runs (and if the models are simple and linear), indicating proportionate contributions to output uncertainty:

- *Coefficient of variation*. The coefficient of variation is the standard deviation normalized to the mean (σ/μ) in order to reduce the possibility that inputs that take on large values are given undue importance.
- *Gaussian approximation.* Another approach to apportioning input variance is Gaussian approximation. Using this method, the variance of a model's output is estimated as the sum of the variances of the inputs (for additive models) or the sum of the variances of the log-transformed inputs (for multiplicative models), weighted by the squares on any constants which may be multiplied by the inputs as they occur in the model.

<u>D.5.3.2 Scatterplots</u>
Cullen and Frey (1999) suggest that a high correlation between an input and an output variable may indicate substantial dependence of the variation in output and the variation of the input. A simple, visual

[10] Related to this issue are the terms "local sensitivity analysis" and "global sensitivity analysis." The former refers to sensitivity analysis conducted around a nominal point of the response surface, while the latter refers to sensitivity analysis across the entire surface.

assessment of the influence of an input on the output is therefore possible using scatterplots, with each plot posing a selected input against the output, as in Figure D.5.3.

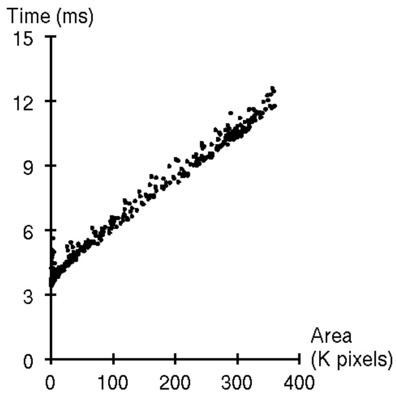


Figure D.5.3. Correlation as indication of input effect. The high correlation between the input variable area and the output variable time (holding all other variables fixed) is an indication of the possible effect of area's variation on the output.

D.5.3.3 Morris's OAT

The key concept underlying one-at-a-time (OAT) sensitivity analyses is to choose a base case of input values and to perturb each input variable by a given percentage away from the base value while holding all other input variables constant. Most OAT sensitivity analysis methods yield *local* measures of sensitivity (see footnote 9) that depend on the choice of base case values. To avoid this bias, Saltelli et al. (2000b) recommend using Morris's OAT for screening purposes because it is a *global* sensitivity analysis method — it entails computing a number of local measures (randomly extracted across the input space) and then taking their average.

Morris's OAT provides a measure of the importance of an input factor in generating output variation, and while it does not quantify interaction effects, it does provide an indication of the presence of interaction. Figure D.5.4 presents the results that one would expect to obtain from applying Morris's OAT (Cossarini et al. 2002). Computational methods for this technique are described in Saltelli et al. 2000b.

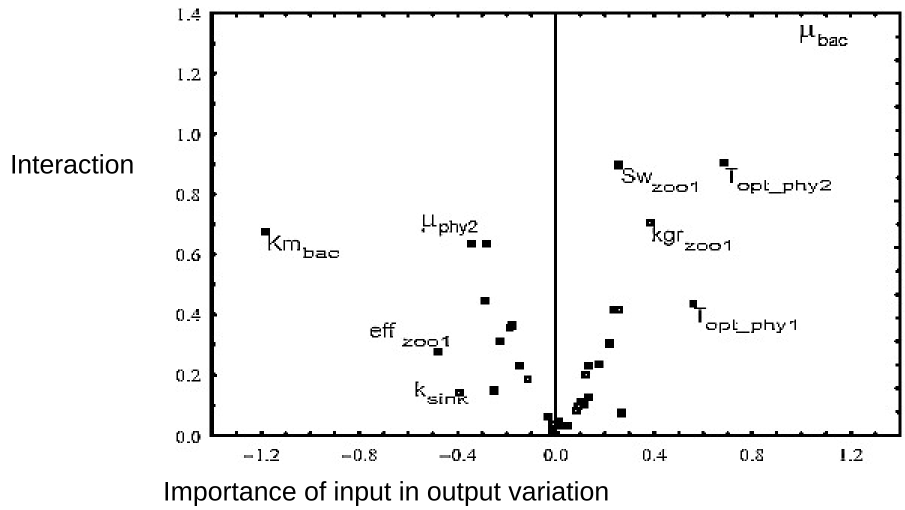


Figure D.5.4. An application of Morris's OAT. Cossarini et al. (2002) investigated the influence of various ecological factors on energy flow through a food web. Their sensitivity analysis indicated that maximum bacteria growth and bacteria mortality (μ_{bac} and Km_{bac}, respectively) have the largest (and opposite) effects on energy flow, as indicated by their values on the horizontal axis. These effects, as indicated by their values on the vertical axis, resulted from interactions with other factors.

D.5.4 Methods Based on Differential Analysis

As noted previously, differential analyses may be used to analyze sensitivity if the analyst is willing either to assume that the model response surface is hyperplanar or to accept that the sensitivity analysis results are local and that they are based on hyperplanar approximations tangent to the response surface at the nominal scenario (Morgan and Henrion 1990; Saltelli et al. 2000b).

Differential analyses entail four steps. First, select base values and ranges for input factors. Second, using these input base values, develop a Taylor series approximation to the output. Third, estimate uncertainty in output in terms of its expected value and variance using variance propagation techniques. Finally, use the Taylor series approximations to estimate the importance of individual input factors (Saltelli et al. 2000b). Computational methods for this technique are described in Morgan and Henrion 1990.

D.5.5 Methods Based on Sampling

One approach to estimating the impact of input uncertainties is to repeatedly run a model using randomly sampled values from the input space. The most well-known method using this approach is Monte Carlo analysis. In a Monte Carlo simulation, a model is run repeatedly. With each run, different input values are drawn randomly from the probability distribution functions of each input, thereby generating multiple output values (Morgan and Henrion 1990; Cullen and Frey 1999). One can view a Monte Carlo simulation as a process through which multiple scenarios generate multiple output values; although each execution of the model run is deterministic, the set of output values may be represented as a cumulative distribution function and summarized using statistical measures (Cullen and Frey 1999).

EPA proposes several best principles of good practice for the conduct of Monte Carlo simulations (EPA 1997). They include the following:

- Conduct preliminary sensitivity analyses to identify significant model components and input variables that make important contributions to model uncertainty.
- When deciding upon a probability distribution function (PDF) for input variables, consider the following questions: Is there any mechanistic basis for choosing a distributional family? Is the PDF likely to be dictated by physical, biological, or other properties and mechanisms? Is the variable

discrete or continuous? What are the bounds of the variable? Is the PDF symmetric or skewed, and if skewed, in which direction?
- Base the PDF on empirical, representative data.
- If expert judgment is used as the basis for the PDF, document explicitly the reasoning underlying this opinion.
- Discuss the presence or absence of covariance among the input variables, which can significantly affect the output.

The preceding points merely summarize some of the main points raised in EPA's Guidance on Monte Carlo Analysis. That document should be consulted for more detailed guidance. Conducting Monte Carlo analysis may be problematic for models containing a large number of input variables. Fortunately, there are several approaches to dealing with this problem:

- *Brute force approach*. One approach is to increase sheer computing power. For example, EPA's ORD is developing a Java-based tool that facilitates Monte Carlo analyses across a cluster of PCs by harnessing the computing power of multiple workstations to conduct multiple runs for a complex model (Babendreier and Castleton 2002).
- *Smaller, structured trials*. The value of Monte Carlo lies not in the randomness of sampling, but in achieving representative properties of sets of points in the input space. Therefore, rather than sampling data from entire input space, computations may be through *stratified sampling* by dividing the input sample space into strata and sampling from within each stratum. A widely used method for stratified sampling is *Latin hypercube sampling,* comprehensively described in Cullen and Frey 1999.
- *Response surface model surrogate*. The analyst may also choose to conduct Monte Carlo not on the complex model directly, but rather on a response surface representation of it. The latter is a simplified representation of the relationship between a selected number of model outputs and a selected number of model inputs, with all other model inputs held at fixed values (Morgan and Henrion 1990; Saltelli et al. 2000b).

D.5.6 Methods Based on Variance

Consider once again a model represented as a function f, with inputs x_1 and x_2 and with output y, such that $y = f(x_1,x_2)$. The input variables are affected by uncertainties and may take on any number of possible values. Let X denote an input vector randomly chosen from among all possible values for x_1 and x_2. The output y for a given X can also be seen as a realization of a random variable Y. Let $E(Y|X)$ denote the expectation of Y conditional on a fixed value of X. If the total variation in y is matched by the variability in $E(Y|X)$ as x_1 is allowed to vary, this is an indication that variation in x_1 significantly affects y.

The variance-based approaches to sensitivity analysis are based on the estimation of what fraction of total variation of y is attributable to variability in $E(Y|X)$ as a subset of input factors are allowed to vary. Three methods for computing this estimation (correlation ratio, Sobol, and Fourier amplitude sensitivity test) are featured in Saltelli et al. 2000b.

D.5.7 Which Method to Use?

A panel of experts was recently assembled to review various sensitivity analysis methods. The panel refrained from explicitly recommending a "best" method and instead developed a list of attributes for preferred sensitivity analysis methods. The panel recommended that methods should preferably be able to deal with a model regardless of assumptions about a model's linearity and additivity, consider interaction effects among input uncertainties, cope with differences in the scale and shape of input PDFs, cope with differences in input spatial and temporal dimensions, and evaluate the effect of an input while all other inputs are allowed to vary as well (Frey 2002; Saltelli 2002). Of the various methods discussed above, only those based on variance (Section D.5.6) are characterized by these attributes. When one or more of the criteria are not important, the other tools discussed in this section will provide a reasonable sensitivity assessment.

As mentioned earlier, choosing the most appropriate sensitivity analysis method will often entail a trade-off between computational complexity, model assumptions, and the amount of information needed from the sensitivity analysis. As an aid to sensitivity analysis method selection, the table below summarizes the features and caveats of the methods discussed above.

Method	Features	Caveats	Reference
Screening methods	May be conducted independent of model run	Potential for significant error if model is non-linear	Cullen and Frey 1999, pp. 247-8.
Morris's one-at-a-time	Global sensitivity analysis	Indicates, but does not quantify interactions	Saltelli et al. 2000b, p. 68.
Differential analyses	Global sensitivity analysis for linear model; local sensitivity analysis for nonlinear model	No treatment of interactions among inputs Assumes linearity, monotonicity, and continuity	Cullen and Frey 1999, pp. 186-94. Saltelli et al. 2000b, pp. 183-91
Monte Carlo analyses	Intuitive No assumptions regarding response surface	Depending on number of input variables, may be time-consuming to run, but methods to simplify are available May rely on assumptions regarding input PDFs	Cullen and Frey 1999, pp. 196-237 Morgan and Henrion 1990, pp. 198-216.
Variance-based	Robust and independent of model assumptions Addresses interactions	May be computationally difficult.	Saltelli et al. 2000b, pp. 167-97

D.6 Uncertainty Analysis

D.6.1 Model Suitability

An evaluation of model suitability to resolve application niche uncertainty (Section 4.1.3.1) should precede any evaluation of data uncertainty and model performance. The extent to which a model is suitable for a proposed application depends on:

- Mapping of model attributes to the problem statement
- The degree of certainty needed in model outputs
- The amount of reliable data available or resources available to collect additional data
- Quality of the state of knowledge on which the model is based
- Technical competence of those undertaking simulation modeling

Appropriate data should be available before any attempt is made to apply a model. A model that needs detailed, precise input data should not be used when such data are unavailable.

D.6.2 Data Uncertainty

There are two statistical paradigms that can be adopted to summarize data. The first employs classical statistics and is useful for capturing the most likely or "average" conditions observed in a given system. This is known as the "frequentist" approach to summarizing model input data. Frequentist statistics rely on measures of central tendency (median, mode, mean values) and represent uncertainty as the deviation from these metrics. A frequentist or "deterministic" model produces a single set of solutions for each model run. In contrast, the alternate statistical paradigm employs a probabilistic framework, which summarizes data according to their "likelihood" of occurrence. Input data are represented as distributions rather than a single numerical value and models outputs capture a range of possible values.

The classical view of probability defines the probability of an event occurring by the value to which the long run frequency of an event or quantity converges as the number of trials increases (Morgan and Henrion 1990). Classical statistics relies on measures of central tendency (mean, median, mode) to define model parameters and their associated uncertainty (standard deviation, standard error, confidence intervals).

In contrast to the classical view, a subjectivist or Bayesian view is that the probability of an event is the current degree of belief that a person has that it will occur, given all of the relevant information currently known to that person. This framework involves the use of probability distributions based on likelihoods functions to represent model input values and employs techniques like Bayesian updating and Monte Carlo methods as statistical evaluation tools (Morgan and Henrion 1990).

Literature Cited

Literature Cited in Main Text and Appendices A, C, D:

Anderson, M., and W. Woessner. 1992. The role of the postaudit in model validation. *Advances in Water Resources* **15:** 167-173.

ANSI (American National Standards Institute). 1994. *Specifications and Guidelines for Quality Systems for Environmental Data Collection and Technology Programs.* ANSI/ANSQ, E4-1994.

ASTM. 2000. *Standard Guide for Statistical Evaluation of Atmospheric Dispersion Model Performance (D 6589).* Available: http://www.astm.org.

Babendreier, J.E., and K.J. Castleton. 2002. Investigating uncertainty and sensitivity in integrated, multimedia environmental models: tools for FRAMES-3MRA. In: *Proceedings of 1st Biennial Meeting of International Environmental Modeling and Software Society* **2:** 90-95. Lugano, Switzerland.

Barnwell, T.O., L.C. Brown, and R.C. Whittemore. 2004. Importance of field data in stream water quality modeling using QUAL2E-UNCAS. *J. Environ. Eng.* **130**(6): 643-647.

Beck, M.B. 1987. Water quality modeling: a review of the analysis of uncertainty. *Water Resources Research* **23**(8): 1393-1442.

Beck, B. 2002. Model evaluation and performance. In: A.H. El-Shaarawi and W.W. Piegorsch, eds. *Encyclopedia of Environmetrics*. Chichester: John Wiley & Sons.

Beck, M., L.A. Mulkey, and T.O. Barnwell. 1994. *Model Validation for Exposure Assessments — DRAFT.* Athens, Georgia: United States Environmental Protection Agency.

Booch, G. 1994. *Object-Oriented Analysis and Design with Applications*. 2nd ed. Redwood, California: Benjamin/Cummings.

Borsuk, M.E., C.A. Stow, and K.H. Reckhow. 2002. Predicting the frequency of water quality standard violations: a probabilistic approach for TMDL development. *Environmental Science and Technology* **36:** 2109-2115.

Bredehoeft, J.D. 2003. From models to performance assessment: the conceptualization problem. *Ground Water* **41**(5): 571-577.

Bredehoeft, J.D. 2005. The conceptualization model problem — surprise. *Hydrogeology Journal* **13**(1): 37-46.

Cossarini, G., C. Solidoro, and A. Crise. 2002. A model for the trophic food web of the Gulf of Trieste. In: A.E. Rizzoli and A.J. Jakeman, eds. *Integrated Assessment and Decision Support: Proceedings of the 1st*

Biennial Meeting of the iEMSs **3:** 485. Available: http://www.iemss.org/iemss2002/proceedings/pdf/volume%20tre/285_cossarini.pdf.

Cox, W.M., and J.A. Tikvart. 1990. A statistical procedure for determining the best performing air quality simulation model. *Atmos. Environ*. **24A**(9):2387-2395.

CREM (Council on Regulatory Environmental Modeling). 2001. *Proposed Agency Strategy for the Development of Guidance on Recommended Practices in Environmental Modeling*. Draft. U.S. Environmental Protection Agency.

Cullen, A.C., and H.C. Frey. 1999. *Probabilistic Techniques in Exposure Assessment: A Handbook for Dealing with Variability and Uncertainty in Models and Inputs.* ed. 326. New York: Plenum Press.

EPA (U.S. Environmental Protection Agency). 1992. *Protocol for Determining the Best Performing Model.* EPA-454-R-92-025. Research Triangle Park, North Carolina: Office of Air Quality Planning and Standards.

EPA (U.S. Environmental Protection Agency). 1993. *Review of Draft Agency Guidance for Conducting External Peer Review of Environmental Regulatory Modeling.* EPA-SAB-EEC-LTR-93-008.

EPA (U.S. Environmental Protection Agency). 1994a. *Peer Review and Peer Involvement at the U.S. Environmental Protection Agency*.

EPA (U.S. Environmental Protection Agency). 1994b. *Report of the Agency Task Force on Environmental Regulatory Modeling: Guidance, Support Needs, Draft Criteria and Charter.* EPA-500-R-94-001. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 1997. *Guiding Principles for Monte Carlo Analysis.* EPA-630-R-97-001. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 1999c. *Description of the MOBILE Highway Vehicle Emissions Factor Model*. Office of Mobile Sources. Ann Arbor, Michigan: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 2000a. *Guidance for the Data Quality Objectives Process.* EPA QA/G-4. Office of Environmental Information.

EPA (U.S. Environmental Protection Agency). 2000b. *Guidance for Data Quality Assessment*. EPA QA/G-9. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 2000c. *Science Policy Council Handbook: Peer Review.* 2nd ed.

EPA (U.S. Environmental Protection Agency). 2000d. *Risk Characterization Handbook*. Science Policy Council. EPA-100-B-00-002. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 2000e. *Policy and Program Requirements for the Mandatory Agency-Wide Quality System.* EPA Order, Classification Number 5360.1 A2.

EPA (U.S. Environmental Protection Agency). 2000f. *EPA Quality Manual for Environmental Programs.* 5360 A1.

EPA (U.S. Environmental Protection Agency). 2001. *Proposed Agency Strategy for the Development of Guidance on Recommended Practices in Environmental Modeling.* Model Evaluation Action Team, Council for Regulatory Environmental Modeling. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 2002a. *Information Quality Guidelines.* Office of Environmental Information. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 2002b. *Quality Assurance Project Plans for Modeling.* EPA QA/G-5M. Office of Environmental Information.

EPA (U.S. Environmental Protection Agency). 2002c. *Guidance on Choosing a Sampling Design for Environmental Data Collection for Use in Developing a Quality Assurance Plan.* EPA QA/G-5S. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 2002d. *Guidance on Environmental Data Verification and Data Validation.* EPA QA/G-8. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 2003a. Revision to guideline on air quality models: adoption of a preferred long range transport model and other revisions. *Federal Register* **68** (72): 18440-18482.

EPA (U.S. Environmental Protection Agency). 2003b. *A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information*. Science Policy Council. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 2006. *Peer Review Handbook*. 3rd ed. EPA-100-B-06-002. Prepared for the U.S. Environmental Protection Agency by members of the Peer Review Advisory Group, for EPA's Science Policy Council. Washington, D.C: U.S. Environmental Protection Agency. Available: http://epa.gov/peerreview/pdfs/Peer%20Review%20HandbookMay06.pdf [accessed Nov. 10, 2006].

Fox, D.G. 1981. Judging air quality model performance: a summary of the AMS workshop on dispersion model performance. *Bull. Amer. Meteor. Soc*. **62:** 599-609.

Frey, H.C. 2002. Guest editorial: introduction to special section on sensitivity analysis and summary of NCSU/USDA Workshop on Sensitivity Analysis. *Risk Analysis.* **22:** 539-546.

Hanna, S.R. 1988. Air quality model evaluation and uncertainty. *Journal of the Air Pollution Control Association* **38:** 406-442.

Hanna, S.R. 1993. Uncertainties in air quality model predictions. *Boundary-Layer Met*. **62:** 3-20.

Hillborn, R., and M. Mangel. 1997. *The Ecological Detective: Confronting Models with Data*. Princeton, New Jersey: Princeton University Press.

Kernigham, B.W., and P.J. Plaugher. 1988. *The Elements of Programming Style*. 2nd ed.

Konikow, L.F., and J.D. Bredehoeft. 1992. Ground water models cannot be validated*. Advances in Water Resources* **15**(1): 75-83.

Levins, S. 1992. The problem of pattern and scale in ecology*. Ecology* **73:** 1943-1967.

Luis, S.J., and D.B. McLaughlin. 1992. A stochastic approach to model validation. *Advances in Water Resources* **15**(1): 75-83.

Manno, J., R. Smardon, J.V. DePinto, E.T. Cloyd, and S. Del Grando. 2008. *The Use of Models in Great Lakes Decision Making: An Interdisciplinary Synthesis.* Randolph G. Pack Environmental Institute, College of Environmental Science and Forestry. Occasional Paper 16.

Morgan, G., and M. Henrion. 1990. The nature and sources of uncertainty. In: *Uncertainty: A Guide to Dealing With Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge, U.K.: Cambridge University Press. pp. 47-72.

NRC (National Research Council). 2001. *Assessing the TMDL Approach to Water Quality Management, Committee to Assess the Scientific Basis of the Total Maximum Daily Approach to Water Pollution Reduction*. Water Science and Technology Board, Division of Earth and Life Studies. Washington, D.C.: National Academies Press.

NRC (National Research Council). 2007. *Models in Environmental Regulatory Decision Making*. Committee on Models in the Regulatory Decision Process, Board on Environmental Studies and Toxicology, Division on Earth and Life Studies. Washington, D.C.: National Academies Press.

Platt, J.R. 1964. Strong inference. *Science* **146:** 347-352.

Press, W.H. 1992. *Numerical Recipes: The Art of Scientific Computing*. Cambridge, U.K.: Cambridge University Press.

Reckhow, K.H. 1994. Water quality simulation modeling and uncertainty analysis for risk assessment and decision making. *Ecological Modeling* **72:** 1-20.

SAB (Science Advisory Board). 1988. *Review of the Underground Storage Tank (UST) Release Simulation Model.* SAB-EEC-88-029. Environmental Engineering Committee. Washington, D.C.: U.S. Environmental Protection Agency.

SAB (Science Advisory Board). 1989. *Resolution on the Use of Mathematical Models by EPA for Regulatory Assessment and Decision-Making*. EPA-SAB-EEC-89-012. Washington, D.C.: U.S. Environmental Protection Agency.

SAB (Science Advisory Board). 1993a. *Review of Draft Agency Guidance for Conducting External Peer Review of Environmental Regulatory Modeling.* EPA-SAB-EEC-LTR-93-008. Washington, D.C.: U.S. Environmental Protection Agency.

SAB (Science Advisory Board). 1993b. *An SAB Report: Review of MMSoils Component of the Proposed RIA for the RCRA Corrective Action Rule.* EPA-SAB-EEC-94-002. Washington, D.C.: U.S. Environmental Protection Agency.

Saltelli, A., S. Tarantola, and F. Campolongo. 2000a. Sensitivity analysis as an ingredient of modeling. *Statistical Science* **15:** 377-395.

Saltelli, A., K. Chan, and M. Scott, eds. 2000b. *Sensitivity Analysis*. New York: John Wiley and Sons.

Saltelli, A. 2002. Sensitivity analysis for importance assessment. *Risk Analysis* **22:** 579-590.

Sargent, R.G. 2000. Verification, validation and accreditation of simulation models. In: J.A. Joines et al., eds. *Proceedings of the 2000 Winter Simulation Conference*.

Scheffe, R.D., and R.E. Morris. 1993. A review of the development and application of the Urban Airshed model. *Atmos. Environ. B-Urb.* **27**(1): 23-39.

Shelly, A., D. Ford, and B. Beck. 2000. *Quality Assurance of Environmental Models*. NRCSE Technical Report Series.

Small, M.J., and P.S. Fishbeck. 1999. False precision in Bayesian updating with incomplete models. *Human and Ecological Risk Assessment* **5**(2): 291-304

Suter, G.W.I. 1993. *Ecological Risk Assessment*. Boca Raton: Lewis Publishers. 528.

Usunoff, E., J. Carrera, and S.F. Mousavi. 1992. An approach to the design of experiments for discriminating among alternative conceptual models. *Advances in Water Resources* **15**(3): 199-214.

Weil, J.C., R.I. Sykes, and A. Venkatram. 1992. Evaluating air-quality models: review and outlook. *J. Appl. Meteor.* **31:** 1121-1145.

Literature Cited in Boxes in Main Text

ADEC (Alaska Department of Environmental Conservation). 2001. Section III.C: Fairbanks Transportation Control Program. In: *State Air Quality Control Plan. Vol. 2. Analysis of Problems, Control Actions.* Adapted July 27, 2001. Juneau, Alaska: Alaska Department of Environmental Conservation.

Beck, M.E. 2002. Environmental foresight and models: a manifesto. *Developments in Environmental Modeling* **22:** 473. Amsterdam: Elsevier.

Burden, D. 2004. Environmental decision making: principles and criteria for groundwater fate and transport models. Presentation at the First Meeting on Models in the Regulatory Decision Process, March 18, 2004, Washington, D.C.

Dennis, R.L. 2002. The ozone problem. In: M.B. Beck, ed. *Environmental Foresight and Models: A Manifesto*. New York: Elsevier. 147-169.

EPA (U.S. Environmental Protection Agency). 1998. *Guidelines for Ecological Risk Assessment.* EPA-630-R-95-002F. Risk Assessment Forum. Available: http://www.epa.gov/superfund/programs/nrd/era.htm [accessed Nov. 7, 2006].

EPA (U.S. Environmental Protection Agency). 2000. *Benchmark Dose Technical Guidance Document.* EPA-630-R-00-001. External Review Draft. Risk Assessment Forum. Washington, D.C.: U.S. Environmental Protection Agency. Available: http://www.epa.gov/nceawww1/pdfs/bmds/BMD-External_10_13__2000.pdf [accessed June 12, 2007].

EPA (U.S. Environmental Protection Agency). 2002b. *Total Maximum Daily Load for Total Mercury in the Ochlockonee Watershed, GA.* Region 4. Available: http://www.epa.gov/Region4/water/tmdl/georgia/ochlockonee/final_tmdls/OchlockoneeHgFinalTMDL.pdf [accessed Nov. 7, 2006].

EPA (U.S. Environmental Protection Agency). 2002c. *Perchlorate Environmental Contamination: Toxicological Review and Risk Characterization.* External Review Draft. NCEA-1-0503. National Center for Environmental Assessment, Office of Research and Development. Washington, D.C.: U.S. Environmental Protection Agency. Available: http://cfpub.epa.gov/ncea/cfm/recordisplay. cfm?deid=24002 [accessed Nov. 7, 2006].

EPA (U.S. Environmental Protection Agency). 2004b. *Final Regulatory Impact Analysis: Control of Emissions From Nonroad Diesel Engines.* EPA-420-R-04-007. Assessment and Standards Division, Office of Transportation and Air Quality. Available: http://www.epa.gov/nonroad-diesel/2004fr/420r04007a.pdf [accessed Nov. 9, 2006].

EPA (U.S. Environmental Protection Agency). 2004c. *Air Quality Criteria for Particulate Matter*. Vols. 1 and 2. EPA-600-P-99-002aF-bF. National Center for Environmental Assessment, Office of Research and Development. Research Triangle Park, North Carolina: U.S. Environmental Protection Agency. Available: http://cfpub.epa.gov/ncea/cfm/partmatt.cfm [accessed Nov. 9, 2006].

EPA (U.S. Environmental Protection Agency). 2005. *Guidance on the Use of Models and Other Analyses in Attainment Demonstrations for the 8-Hour Ozone NAAQS.* Draft Final. Office of Air and Radiation, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina: U.S. Environmental Protection Agency. Available: http://www.epa.gov/ttn/scram/guidance/guide/draft-final-o3.pdf [accessed April 27, 2007].

Fenner, K., M. Scheringer, M. MacLeod, M. Matthies, T. McKone, M. Stroebe, A. Beyer, M. Bonnell, A.C. Le Gall, J. Klasmeier, D. Mackay, D. van de Meent, D. Pennington, B. Scharenberg, N. Suzuki, and F. Wania. 2005. Comparing estimates of persistence and long-range transport potential among multimedia models. *Environ. Sci. Technol.* **39**(7): 1932-1942.

George, J. 2004. State perspective on modeling in support of the TMDL program. Presentation at the First Meeting on Models in the Regulatory Decision Process, March 18, 2004, Washington, D.C.

Gilliland, A. 2003. Overview of model Evaluation Plans for CMAQ FY04 Release. Presented at the CMAQ Model Peer Review Meeting, December 17, 2003, Research Triangle Park, NC. Available: http://www.cmascenter.org/r_and_d/first_review/pdf/model_evaluation_plans_for_cmaq04_(gilliland).pdf?temp_id=99999 [accessed Nov. 22, 2006].

Klasmeier, J., M. Matthies, M. MacLeod, K. Fenner, M. Scheringer, M. Stroebe, A.C. Le Gall, T.E. McKone, D. van de Meent, and F. Wania. 2006. Application of multimedia models for screening assessment of long-range transport potential and overall persistence. *Environ. Sci. Technol.* **40**(1): 53-60.

Leighton, P.A. 1961. Photochemistry of Air Pollution. New York: Academic Press.

Morales, K.H., L. Ryan, T.L. Kuo, M.M. Wu, and C.J. Chen. 2000. Risk of internal cancers from arsenic in drinking water. *Environ. Health Perspect.* **108**(7): 655-661.

Morales, K.H., J.G. Ibrahim, C.J. Chen, and L.M. Ryan. 2006. Bayesian model averaging with applications to benchmark dose estimation for arsenic in drinking water. *J. Am. Stat. Assoc.* **101**(473): 9-17.

NRC (National Research Council). 1991. *Rethinking the Ozone Problem in Urban and Regional Air Pollution.* Washington, D.C.: National Academies Press.

NRC (National Research Council). 2001b. *Arsenic in Drinking Water 2001 Update.* Washington, D.C.: National Academies Press.

NRC (National Research Council). 2003. *Adaptive Monitoring and Assessment for the Comprehensive Everglades Restoration Plan.* Washington, D.C.: National Academies Press.

NRC (National Research Council). 2005a. *Superfund and Mining Megasites.* Washington, D.C.: National Academies Press.

NRC (National Research Council). 2005b. *Health Implications of Perchlorate Ingestion.* Washington, D.C.: National Academies Press.

NRC (National Research Council). 2007. *Models in Environmental Regulatory Decision Making*. Committee on Models in the Regulatory Decision Process, Board on Environmental Studies and Toxicology, Division on Earth and Life Studies. Washington, D.C.: National Academies Press.

OECD (Organisation for Economic Co-operation and Development). 2002. *Report of the OECD/UNEP Workshop on the Use of Multimedia Models for Estimating Overall Environmental Persistence and Long-Range Transport Potential in the Context of PBTs/POPs Assessment.* ENV/JM/MONO (2002)15. OECD Series on Testing and Assessment No. 36. Paris: Organisation for Economic Co-operation and Development. Available: http://www.olis.oecd.org/olis/2002doc.nsf/43bb6130e5e86e5fc12569fa005d004c/150147753d5c7f6cc1256c010047d31d/$FILE/JT00130274.PDF [accessed April 27, 2007].

Oreskes, N.M., K. Shrader-Frechette, and K. Belitz. 1994. Verification, validation and confirmation of numerical models in the earth sciences. *Science* **263:** p. 641-646.

Scheringer, M., M. MacLeod, and F. Wegmann. 2006. *The OECD Pov and LRTP Screening Tool, Version 2.0. — Software and Manual.* http://www.sust-chem.ethz.ch/downloads/Tool2_0_Manual.pdf [accessed April 27, 2007].

Shoemaker, L. 2004. Modeling and decision making overview. Presentation at the First Meeting on Models in the Regulatory Decision Process, March 18, 2004, Washington, D.C.

Suter, G.W.I. 1993. *Ecological Risk Assessment*. Boca Raton: Lewis Publishers. 528.

TCEQ (Texas Commission on Environmental Quality). 2004. Required control strategy elements. Chapter 5. In: *Revision to the State Implementation Plan (SIP) for the Control of Ozone Air Pollution: Houston/Galveston/Brazoria Ozone Nonattainment Area.* Project No. 2004-042-SIP-NR. Austin, Texas: Texas Commission on Environmental Quality. Available: http://www.tnrcc.state.tx.us/oprd/sips/june2004hgb_EDrec.html#docs [accessed June 8, 2005].

Volinsky, C.T., D. Madigan, A.E. Raftery, and R.A. Kronmal. 1997. Bayesian model averaging in proportional hazard models: assessing the risk of the stroke. *Appl. Statist.* **46**(4): 433-448.

Weaver, J. 2004. Modeling leaking underground storage tanks. Presentation at the First Meeting on Models in the Regulatory Decision Process, March 18, 2004, Washington, D.C.

Wool, T. 2004. Overview of the TMDL program and modeling approaches. Presentation at the First Meeting on Models in the Regulatory Decision Process, March 18, 2004, Washington, D.C.

Literature Cited in Appendix B

Birgand, F. 2004. Evaluation of QUAL2E. In: J.E. Parsons, D.L. Thomas, and R.L. Huffman, eds. *Agricultural Non-Point Source Water Quality Models: Their Use and Application*. Southern Cooperative Series Bulletin 398. 96-106. Available: http://www3.bae.ncsu.edu/Regional-Bulletins/Modeling-Bulletin/qual2e.html.

Brown, L.C. 1986. *Uncertainty Analysis Using QUAL2E.* EPA-600-D-86-053. Office of Research and Development, U.S. Environmental Protection Agency.

Brown, L.C., and T.O. Barnwell. 1987. *The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual.* EPA-600-3-87-007. Environmental Research Laboratory. Athens, Georgia: U.S. Environmental Protection Agency.

Byun, D.W., and J.K.S. Ching. 1999. *Science Algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System.* EPA-600-R-99-030. Atmospheric Modeling Division, National Exposure Research Laboratory. Research Triangle Park, North Carolina: U.S. Environmental Protection Agency. Available: http://www.epa.gov/asmdnerl/CMAQ/CMAQscienceDoc.html [accessed June 13, 2007].

Caliper Corporation. 2007. *TransCAD.* Available: http://www.caliper.com/tcovu.htm [accessed June 13, 2007].

Coulter, C.T. 2004. *EPA-CMB8.2 Users Manual.* EPA-452-R-04-011. Air Quality Modeling Group, Emissions, Monitoring and Analysis Division, Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina: U.S. Environmental Protection Agency. Available: http://www.epa.gov/scram001/models/receptor/EPACMB82Manual.pdf [accessed June 13, 2007].

Donigian, A.S., Jr. 2002. *Watershed Model Calibration and Validation: The HSPF Experience*. WEF National TMDL Science and Policy 2002, November 13-16, 2002. Phoenix, AZ. Available: http://hspf.com/TMDL.Nov02.Donigian.Paper.doc [accessed June 13, 2007].

EIA (Energy Information Administration). 1993. *Documentation of the DRI Model of the U.S. Economy.* Available: tonto.eia.doe.gov/FTPROOT/modeldoc/m061.pdf [accessed March 31, 2007].

EPA (U.S. Environmental Protection Agency). 1994. *Guidance Manual for the Integrated Exposure Uptake Biokinetic Model for Lead in Children.* EPA-540-R-93-081. OSWER9285.7-15-1. PB93-963510. Office of Solid Waste and Emergency Response. Washington, D.C.: U.S. Environmental Protection Agency. Available: http://www.epa.gov/superfund/programs/lead/products.htm [accessed Nov. 2, 2006].

EPA (U.S. Environmental Protection Agency). 1998. *BIOPLUME III: Natural Attenuation Decision Support System. User's Manual Version 1.0*. EPA-600-R-98-010. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 1999. *ABEL Model*. Environmental Data Registry. Available: http://iaspub.epa.gov/edr/edr_proc_qry.navigate?P_LIST_OPTION_CD=CSDIS&P_REG_AUTH_IDENTIFIER=1&P_DATA_IDENTIFIER=90389&P_VERSION=1 [accessed June 14, 2007].

EPA (U.S. Environmental Protection Agency). 2000. *Benchmark Dose Technical Guidance Document.* EPA-630-R-00-001. External Review Draft. Risk Assessment Forum. Washington, D.C.: U.S. Environmental Protection Agency. Available: http://www.epa.gov/nceawww1/pdfs/bmds/BMDExternal_10_13_2000. pdf [accessed June 12, 2007].

EPA (U.S. Environmental Protection Agency). 2001. *PLOAD Version 3.0: An ArcView GIS Tool to Calculate Nonpoint Sources of Pollution in Watershed and Stormwater Projects*. User's Manual. Office of Water Science. Available: www.epa.gov/waterscience/basins/b3docs/PLOAD_v3.pdf [accessed March 21, 2007].

EPA (U.S. Environmental Protection Agency). 2004. *MOVES2004 User Guide.* Draft. EPA-420-P-04-019. Assessment and Standards Division, Office of Transportation and Air Quality. Washington, D.C.: U.S. Environmental Protection Agency. Available: http://www.epa.gov/otaq/models/ngm/420p04019.pdf [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2005a. *User's Guide for the Final NONROAD2005 Model.* EPA-420-R-05-013. Assessment and Standards Division, Office of Transportation and Air Quality. Washington, D.C.: U.S. Environmental Protection Agency. Available: http://www.epa.gov/otaq/models/nonrdmdl/nonrdmdl2005/420r05013.pdf [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2005b. *PRZM-3, A Model for Predicting Pesticide and Nitrogen Fate in the Crop Root and Unsaturated Soil Zones: Users Manual for Release 3.12.2.* EPA-600-R-05-111. Washington, D.C.: U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency). 2005c. *Integrated Exposure Uptake Biokinetic Model for Lead in Children, Windows Version (IEUBKwin v1.0 build 263).* Superfund. Available: http://www.epa.gov/superfund/programs/lead/products.htm#ieubk [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2005d. *Economic Impact Analysis of the Standards of Performance for Stationary Compression Ignition Internal Combustion Engines.* EPA-452-R-05-006. Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina: U.S. Environmental Protection Agency. Available: http://www.epa.gov/ttn/atw/nsps/cinsps/ci_nsps_eia_reportfinalforproposal.pdf [accessed June 14, 2007].

EPA (U.S. Environmental Protection Agency). 2006a. *Biogenic Emissions Inventory System (BEIS) Modeling.* Atmospheric Sciences Modeling Division, Office of Research and Development. Available: http://www.epa.gov/asmdnerl/biogen.html [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2006b. *NONROAD Model (Nonroad Engines, Equipment, and Vehicles).* Office of Transportation and Air Quality. Available: http://www.epa.gov/otaq/nonrdmdl.htm [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2006c. *CSMoS Ground-Water Modeling Software.* Ground Water Technical Support Center, Risk Management Research, Office of Research and Development. Available: http://www.epa.gov/ada/csmos/models.html [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2006d. HSPF. *Exposure Assessment Models*. Available: http://www.epa.gov/ceampubl/swater/hspf/ [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2006e. *Water Quality Analysis Simulation Program (WASP).* Ecosystems Research Division, Office of Research and Development. Available: http://www.epa.gov/athens/wwqtsc/html/wasp.html [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2006f. *The Chemical Mass Balance (CMB) Model EPA-CMBv8.2.* Receptor Modeling, Air Quality Models. Available: http://www.epa.gov/scram001/receptor_cmb.htm [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2006g. *AQUATOX.* Office of Water Science. Available: http://www.epa.gov/waterscience/models/aquatox/ [accessed June 14, 2007].

EPA (U.S. Environmental Protection Agency). 2006h. *BASS.* Ecosystems Research Division, Office of Research and Development. Available: http://www.epa.gov/athens/research/modeling/bass.html [accessed June 14, 2007].

EPA (U.S. Environmental Protection Agency). 2007a. *Better Assessment Science Integrating Point & Nonpoint Sources (BASINS)*. Water Quality Models and Tools, Office of Water Science. Available: http://www.epa.gov/waterscience/basins/ [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2007b. *MOBILE6 Vehicle Emission Modeling Software.* Office of Transportation and Air Quality. Available: http://www.epa.gov/otaq/m6.htm [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2007c. *Modeling Products.* Exposure Assessment. Available: http://www.epa.gov/ceampubl/products.htm [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2007d. *Community Multiscale Air Quality (CMAQ).* Atmospheric Science Modeling, Office of Research and Development. Available: http://www.epa.gov/asmdnerl/CMAQ/index.html [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2007e. *Human Exposure Modeling — Air Pollutants Exposure Model (APEX/TRIM.Expo$_{Inhalation}$).* Office of Air and Radiation. Available: http://www.epa.gov/ttn/fera/human_apex.html [accessed June 13, 2007].

EPA (U.S. Environmental Protection Agency). 2007f. *Benchmark Dose Software*. National Center for Environmental Assessment, Office of Research and Development. Available: http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=164443 [accessed June 14, 2007].

EPA (U.S. Environmental Protection Agency). 2007g. *SERAFM — Spreadsheet-based Ecological Risk Assessment for the Fate of Mercury*. Surface Water Models. Exposure Assessment Models. Available: http://www.epa.gov/ceampubl/swater/serafm/index.htm [accessed June 14, 2007].

EPA (U.S. Environmental Protection Agency). 2007h. *Program to Assist in Tracking Critical Habitat (PATCH)*. Western Ecology Division, Office of Research and Development. Corvallis, Oregon: U.S. Environmental Protection Agency. Available: http://www.epa.gov/wed/pages/models/patch/patchmain.htm [accessed June 14, 2007].

EPA (U.S. Environmental Protection Agency). 2007i. *Benefits Analysis Models/Tools.* Economics and Cost Analysis Support. Available: http://www.epa.gov/ttnecas1/benmodels.html [accessed June 14, 2007].

Glover, E.L., and M. Cumberworth. 2003. *MOBILE6.1 Particulate Emission Factor Model Technical Description — Final Report.* EPA-420-R-03-001. Assessment and Standards Division, Office of Transportation and Air Quality. Available: http://www.epa.gov/otaq/models/mobile6/r03001.pdf [accessed June 13, 2007].

Hawkins, T. 2005. *Critical Evaluation of the Aquatox Model.* Carnegie Mellon University. Available: http://www.ce.cmu.edu/~trh/Professional/Research/Hawkins_CriticalEvaluationOfTheAquatoxModel.pdf [accessed March 31, 2007].

Hayes, J.T., P.A. O'Rourke, W.H. Terjung, and P.E. Todhunter. 1982. A feasible crop yield model for worldwide international food production. *Int. J. Biometeorol.* **26**(3): 239-257.

ICF Consulting. 2005. *User's Guide to the Regional Modeling System for Aerosols and Deposition (REMSAD): Version 8*. Available: http://www.remsad.com/documents/remsad_users_guide_v8.00_112305.pdf [accessed March 31, 2007].

ICF International/Systems Applications International. 2006. *Regional Modeling System for Aerosols and Deposition (REMSAD)*. Available: http://www.remsad.com/ [accessed June 13, 2007].

Knightes, C.D. 2005. SERAFM: An ecological risk assessment tool for evaluating wildlife exposure risk associated with mercury-contaminated sediment in lake and river systems. Presentation at EPA Science Forum 2005, May 16-18, 2005, Washington, D.C.

Lawler, J.J., D. White, R.P. Neilson, and A.R. Blaustein. 2006. Predicting climate-induced range shifts: model differences and model reliability. *Glob. Change Biol.* **12**(8):1568-1584.

Lifeline Group, Inc. 2006. *Users Manual: LifeLine™ Verson 4.3*. Software for Modeling Aggregate and Cumulative Exposures to Pesticides and Chemicals. Available: http://www.thelifelinegroup.org/lifeline/documents/v4.3_UserManual.pdf [accessed March 31, 2007].

Lifeline Group, Inc. 2007. Lifeline software. Available: http://www.thelifelinegroup.org/index.htm [accessed June 13, 2007].

MBL (Marine Biological Laboratory). 2005. Marine Biological Laboratory General Ecosystem Model (MBL-GEM). The Ecosystem Center, Marine Biological Laboratory. Available: http://ecosystems.mbl.edu/Research/Models/gem/welcome.html [accessed June 13, 2007].

MIT (Massachusetts Institute of Technology). 2006. Natural Emissions Model (NEM). *The MIT Integrated Global System Model: Ecosystems Impacts.* Available: http://web.mit.edu/globalchange/www/tem.html#nem [accessed June 13, 2007].

Parkhurst, D.L., D.C. Thoratenson, and L.N. Plummer. 1980. *PHREEQE: A Computer Program for Geochemical Calculations.* U.S. Geological Survey Water Research Investigations 80-96. Reston, Virginia: U.S. Geological Survey.

Prudic, D.E., L.F. Konikow, and E.R. Banta. 2004. *A New Stream- Flow Routing (SFR1) Package to Simulate Stream-Aquifer Interaction With MOD-FLOW-2000.* U.S. Geological Survey Open-File Report 2004-1042. U.S. Department of the Interior, U.S. Geological Survey. Available: http://pubs.usgs.gov/of/2004/1042/ [accessed June 13, 2007].

Rashleigh, B. 2007. Assessment of lake ecosystem response to toxic events with the AQUATOX model. In: I.E. Gonenc, V. Koutitonsky, B. Rashleigh, R.A. Ambrose, and J.P. Wolfin, eds. *Assessment of the Fates and Effects of Toxic Agents on Water Resources.* Dordrecht, The Netherlands: Springer. 293-299.

Richmond, H., T. Palma, G. Glen, and L. Smith. 2001. *Overview of APEX (2.0): EPA's Pollutant Exposure Model for Criteria and Air Toxic Inhalation Exposures.* Annual Meeting of the International Society of Exposure Analysis, November 4-8, 2001, Charleston, South Carolina.

Ritchie, J.T., and D. Godwin. 2007. *CARES Wheat 2.0.* Michigan State University. Available: http://nowlin.css.msu.edu/wheat_book/ [accessed June 14, 2007].

Schwarz, G.E., A.B. Hoos, R.B. Alexander, and R.A. Smith. 2006. *The SPARROW Surface Water-Quality Model: Theory, Application and User Documentation.* U.S. Geological Survey Techniques and Methods 6-B3. U.S. Geological Survey. Available: http://pubs.usgs.gov/tm/2006/tm6b3/PDF.htm [accessed March 31, 2007].

Shiftan, Y., and J. Suhrbier. 2002. The analysis of travel and emission impacts of travel demand management strategies using activity-based models. *Transportation* **29**(2): 145-168.

Sokolov, A.P., C.A. Schlosser, S. Dutkiewicz, S. Paltsev, D.W. Kicklighter, H.D. Jacoby, R.G. Prinn, C.E. Forest, J. Reilly, C. Wang, B. Felzer, M.C. Sarofim, J. Scott, P.H. Stone, J.M. Melillo, and J. Cohen. 2005. *The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation.* Report No. 124. Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology. Available: http://web.mit.edu/globalchange/www/abstracts.html#a124 [accessed March 31, 2007].

Systems Applications International, Inc. 1999. *User's Guide to the Variable-Grid Urban Airshed Model (UAM-V).* San Rafael, California: Systems Applications International, Inc. Available: http://www.uamv.com/documents/uam-v_1.31_user's_guide.pdf [accessed June 13, 2007].

USGS (U.S. Geological Survey). 2007a. *SPARROW Modeling of Surface-Water Quality.* U.S. Department of the Interior, U.S. Geological Survey. Available: http://water.usgs.gov/nawqa/sparrow/ [accessed June 13, 2007].

USGS (U.S. Geological Survey). 2007b. *MODFLOW-2000 Version 1.17.02.* USGS Ground-Water Software. U.S. Department of the Interior, U.S. Geological Survey. Available: http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html [accessed June 13, 2007].

Vukovich, J.M., and T. Pierce. 2002. *The Implementation of BEIS3 Within the SMOKE.* 11th International Emission Inventory Conference: Emission Inventories — Partnering for the Future, April 15-18, 2002, Atlanta, Georgia. Available: http://www.epa.gov/ttn/chief/conference/ei11/modeling/vukovich.pdf [accessed June 13, 2007].

Wilson, J.D., and R.L. Naff. 2004. *MODFLOW-2000: The U.S. Geological Survey Modular Ground-Water Model-GMG Linear Equation Solver Package Documentation.* U.S. Geological Survey Water Resources Open-File Report 2004-1261. U.S. Department of the Interior, U.S. Geological Survey. Available: http://pubs.usgs.gov/of/2004/1261/ [accessed June 13, 2007].

Young, T., R. Randolph, and D. Bowman. 1994. *Economic Growth Analysis System: Version 2.0.* EPA-600-SR-94-139. Air and Energy Engineering, Research Laboratory. Research Triangle Park, North Carolina: U.S. Environmental Protection Agency. Available: http://www.p2pays.org/ref/07/0622.pdf [accessed June 13, 2007].

EPA/100/K-09/003 Guidance on the Development, Evaluation, and Application of Environmental Models

United States
Environmental Protection
Agency

Office of the Science Advisor (8105R)
Washington, DC 20460

RESEARCH

Effect of urban soil compaction on infiltration rate

J.H. Gregory, M.D. Dukes, P.H. Jones, and G.L. Miller

ABSTRACT: Inadvertent soil compaction at the urban lot scale is a process that reduces infiltration rates, which can lead to increased stormwater runoff. This is particularly important in low impact development strategies where stormwater is intended to infiltrate rather than flow through a traditional stormwater network to a detention basin. The effect of compaction on infiltration rates on sandy soils in North Central Florida was measured with a double ring infiltrometer on urban construction sites and across various levels of compaction. Average non-compacted infiltration rates ranged from 377 to 634 mm hr^{-1} (14.8 to 25.0 in hr^{-1}) for natural forest, from 637 to 652 mm hr^{-1} (25.1 to 25.7 in hr^{-1}) for planted forest, and 225 mm hr^{-1} (8.9 in hr^{-1}) for pasture sites. Average infiltration rates on compacted soils ranged 8-175 mm hr^{-1} (0.3-6.9 in hr^{-1}), 160 to 188 mm hr^{-1} (6.3 to 7.4 in hr^{-1}), and 23 mm hr^{-1} (0.9 in hr^{-1}) for the same respective sites. Although there was wide variability in infiltration rates across both compacted and non-compacted sites, construction activity or compaction treatments reduced infiltration rates 70 to 99 percent. Maximum compaction as measured with a cone penetrometer occurred in the 20 to 30 cm (7.9 to 11.8 in) depth range. When studying the effect of different levels of compaction due to light and heavy construction equipment, it was not as important how heavy the equipment was but whether compaction occurred at all. Infiltration rates on compacted soils were generally much lower than the design storm infiltration rate of 254 mm hr^{-1} (10.0 inches hr^{-1}) for the 100-yr, 24-hr storm used in the region. This implies that construction activity in this region increases the potential for runoff and the need for large stormwater conveyance networks not only due to the increase in impervious area associated with development but also because the compacted pervious area effectively approaches the infiltration behavior of an impervious surface.

Keywords: Compaction, cone index, double ring, infiltration, LID, low impact development, penetrometer, stormwater

Urban areas in Florida are rapidly expanding, with Florida accounting for approximately 11 percent of all new homes constructed in the United States in 2003 (U.S. Census Bureau, 2004). Soil compaction is associated with this urban development. Compaction can be the intentional compacting of a site to increase the structural strength of the soil or it can be inadvertently caused by the use of heavy equipment and grading of lots. Soil compaction affects the physical properties of soil by increasing its strength and bulk density, decreasing its porosity, and forcing a smaller distribution of pore sizes within the soil. These changes affect the way in which air and water move through the soil and the ability of roots to grow in the soil (NRCS, 2000; Richard et al., 2001).

Changes to the way that air and water move within the soil can affect infiltration rate. A decrease in infiltration rate will result in increased runoff volume, greater flooding potential and reduced groundwater recharge within watersheds. Compaction has a significant influence on soil hydraulic properties such as soil water retention, soil water diffusivity, unsaturated hydraulic conductivity and saturated hydraulic conductivity (Horton et al., 1994). These hydraulic properties in turn govern infiltration rates.

The infiltration of stormwater within urban areas is an important process being promoted as part of a new stormwater management strategy. This management strategy is often referred to as low impact development, which aims to reduce the volumes and peaks of runoff to predevelopment levels (Price George's County, 1999). Promoting infiltration is one of the primary methods for achieving this goal. The quantification of the effect of compaction on infiltration rates is therefore, an important task.

Quantifying the effect of compaction in urban areas has generally consisted of surveys that have measured infiltration rates and then related these measured infiltration rates to land development, land types, or levels of compaction. Research into the effects of soil compaction on infiltration rate has been conducted in Pennsylvania (Felton and Lull, 1963; Hamilton and Waddington, 1999), Wisconsin (Kelling and Peterson, 1975), North Carolina (Kays, 1980) and Alabama (Pitt et al., 1999). These studies have shown that soil infiltration rates are negatively affected by the compaction associated with urban development. However, these studies did not relate specific levels of compaction to infiltration rate. Although development is occurring at a rapid pace in Florida, studies have not been conducted to characterize infiltration rates as affected by compaction during development activities. It is often assumed that infiltration rate far exceeds precipitation rate due to the coarse soils found in many areas of the state. The hypothesis of this research is that compaction during typical construction practices result in a substantial reduction in infiltration rate on sandy soils.

The objectives of this research were to: 1) quantify the effect of compaction due to construction activities on infiltration rates of typical urban development sites on sandy soils in North Central Florida, and 2) determine the effect of various levels of compaction on infiltration rates of sandy urban development sites as compared to uncompacted infiltration rates.

Justin H. Gregory is a former graduate research assistant in the Agricultural and Biological Engineering Department at the University of Florida in Gainesville, Florida. **Michael D. Dukes** is the corresponding author and assistant professor in the Agricultural and Biological Engineering Department at the University of Florida in Gainesville, Florida. **Pierce H. Jones** is a professor and director of the program for resource efficient communities at the University of Florida in Gainesville, Florida. **Grady L. Miller** is an associate professor in the Environmental Horticulture Department at the University of Florida in Gainesville, Florida.

Materials and Methods

Compaction due to construction activities. *Site description.* A natural, mixed wood forest site in the Madera subdivision of Gainesville, Florida was chosen as a research site. Lots 2, 3, 4, 8, and 12 of the Madera development were chosen because they were undisturbed lots that had not been cleared or subjected to vehicle traffic. Lot 24 of the Madera development was chosen because it was used as an access to a detention pond and for parking heavy construction vehicles. As a result, this lot was made up of areas that had been compacted due to construction vehicle traffic next to areas that were undisturbed due to the wooded conditions. Madera lots 2, 3, 4, 8, 12, and 24 will be referred to as natural wooded lots A, B, C, D, E, and F. The soil classification for this area is a Bonneau fine sand (Arenic Paleudult; USDA, 1985) and according to data in the literature is 89.3 percent sand, 10.6 percent silt, has a field capacity of 18.9 percent by volume, and has a saturated hydraulic conductivity of 103 mm hr^{-1} in the top 23 cm (Carlisle et al., 1989).

The Mentone development of Gainesville, Florida was also chosen as a research site. The predevelopment vegetation was planted slash pine (*Pinus elliottii*), which was at least 10 years old. Compaction testing was carried out on lot 818 and lot 857. Lot 818 was chosen because it was a lot that had been partially cleared to allow access for the construction of one of the detention ponds. Lot 857 was chosen because it had been used to park heavy construction equipment and was used by construction vehicles as a shortcut between adjacent streets. Both lots were made up of areas that had been compacted and areas that were undisturbed similar to Madera lot 24 (lot F) as described previously. Mentone lots 857 and 818 will be referred to as planted forest lots G and H. The soil on lots G and H are classified as an Apopka fine sand (Grossarenic Paleudult; USDA, 1985) and according to data in the literature is 96.2 percent sand, 1.8 percent silt, has a field capacity of 11.7 percent by volume, and has a saturated hydraulic conductivity of 197 mm/hr in the top 20 cm (Carlisle et al., 1989).

Undisturbed infiltration rates. From December 2002 through February 2003, predevelopment infiltration rates were measured on wooded lots A, B, C, and E. Sixteen infiltration tests and sixteen bulk density and gravimetric soil moisture content measurements were conducted on each of these lots in areas that would eventually be landscaped after home construction. Infiltration rates were measured using a constant head double ring infiltrometer with inner and outer ring diameters of 15 cm (5.9 in) and 30 cm (11.8 in) that was inserted to a depth of approximately 10 cm (3.9 in). The constant head was maintained with a Mariotte siphon and the volume of water required to maintain this head was measured at a one-minute interval. A detailed description of the infiltration apparatus is described by Gregory et al. (2005). The infiltration tests were conducted for at least 40 min (infiltration rates were found to become constant typically within the first 10 minutes of the test or less). Cumulative infiltration was plotted against time and the data was fitted to the Philip's infiltration equation as follows,

$$I = Kt + St^{1/2} \qquad (1)$$

where,

I = cumulative infiltration depth (mm),

K = saturated hydraulic conductivity (mm hr^{-1}),

t = time (hr), and

S = soil water sorptivity (mm hr^{-1}).

Values of the parameters K and S can be found by regressing the cumulative infiltration data collected in the field to Equation 1 (Lal and Vandoren, 1990). The parameter K from the Philips infiltration equation was used as an approximation for the steady state infiltration rate (Chow et al., 1988). The infiltration rates reported in this paper are the K parameter from the Philips infiltration equation.

Soil bulk density and gravimetric moisture content were measured using a standard intact core method in the top 5 cm of (2 in) soil after any decaying organic matter was removed. Volumetric moisture content was then determined as the product of the bulk density and the gravimetric moisture content (ASTM, 2002a; Blake and Hartge, 1986; ASTM, 2002b; Gardner, 1986). The cone index (ASAE, 2000) was also measured near the infiltration measurement locations using a Spectrum™ SC900 Soil Compaction Meter (Spectrum Technologies, Inc., Plainfield, Illinois), which recorded cone index in increments of 2.5 cm (1 in) up to 45 cm (17.7 in). A standard cone (ASAE, 2000) was used to determine cone index. Five cone index measurements were made near the location of each infiltrometer test.

Post development infiltration rates. Post development infiltration tests were carried out on natural wooded lot A in May 2004 since this was the only lot with a finished home during the time of this study. Infiltration rates were measured at four locations on the turf area in the front yard and four sites on the turf area in the backyard. These infiltration tests and cone index measurements were carried out using the procedure described previously.

Side-by-side testing. Infiltration, cone index, and bulk density measurements were conducted on the natural wooded lot F and the planted forest lots G and H. The testing was carried out February through July 2003. On each lot, six sites were selected for paired measurement testing. Each site consisted of a location that was undisturbed and a location that had been trafficked by construction vehicles. There was a maximum distance of 2 m (6.6 ft) between the paired measurement locations at each site. On the planted forest lot H the cone index was measured at only four of the sites due to interference of clearing operations on the other two sites. A particle size distribution analysis was conducted using the hydrometer method on five soil samples collected randomly (from the top 10 cm) on each lot (Gee and Bauder, 1986). A t-test was used to compare the paired infiltration rate and bulk density measurements.

Effects of compaction level on infiltration rates. *Site description.* An existing pasture at the University of Florida Plant Science Research and Education Unit near Citra, Florida was used for a compaction trial. The pasture area had been subjected to traffic particular to this land use for at least 20 years. This site represents pastures in Florida that are being converted to residential subdivisions and will be referred to as the pasture site in this paper. The soil has been mapped as a Candler fine sand (Lamellic Quartzipsamments; Buster, 1979), which is composed of 96.4 percent sand, 2.0 percent silt, and has a field capacity of 6.2 percent by volume in the top 25 cm (Carlisle et al., 1989).

Controlled compaction. A controlled compaction trial was carried out on the pasture site in February 2004. An area of the pasture approximately 5 m (16.4 ft) long by 2.5 m (8.2 ft) wide was cleared of the top 10 cm (3.9 in) of grass roots (a typical practice on construction sites). This area was then divided into sixteen plots each 0.6 m (2.0 ft) by 1.2 m (3.9 ft). Four levels of compaction treatments were then applied in a Latin Square experimental design. A Mikasa GX100 (MT-65H) (Mikasa Sangyo Co., Ltd.) 'jumping jack' type compactor was used to apply different levels of compaction. The compactor was moved about the plots in a steady manner to achieve a uniform level of compaction. The four levels of compaction were zero minutes of compaction (control), a half-minute of compaction, three minutes of compaction and ten minutes of compaction. Infiltration rate, bulk density, soil moisture content, and cone index were measured on each plot by methods described previously. Also, a Proctor density test (ASTM, 2002c) was conducted on a soil sample from the site. The experimental procedure was then repeated in an undisturbed area on lot D after removal of the top 10 cm (3.9 in) of organic material and soil. Thus, the two common areas being developed in North Central Florida were represented by these two sites. The results from the two locations were analyzed using the GLM procedure with an analysis of variance (ANOVA; SAS, 2001). Duncan's Multiple Range Test at the 95 percent confidence interval was used to find significant differences between the treatment means.

Vehicular compaction. A pasture area at the Plant Science Research and Education Unit was selected and a mechanical grader was used to remove the top 10 cm (3.9 in) of grass and soil from three plots each about 18 m (59.0 ft) long and 1.2 m (3.9 ft) wide. It took approximately four passes of the grader to remove the grass roots and soil and care was taken to ensure that the grader traveled in the same wheel tracks for each pass, thus ensuring that there was minimal compaction within the plots.

Three vehicles that are commonly used in urban construction were used for the vehicular compaction trial. These vehicles were an all-wheel drive Caterpillar 416B backhoe weighing 6.3 Mg (7.1 t) with a front tire pressure of 206 kPa (30 psi) and a rear tire pressure of 310 kPa (45 psi), a dump truck with a front axle weight of 6.0 Mg (6.7 t), a total load of 18.4 Mg (20.6 t) on the two rear axles and tire pressures of 310 kPa (45 psi) and a pickup truck with a front axle load of 1.1 Mg (1.2 tons), a rear axle load of 0.8 Mg (0.9 tons) and a tire pressure of 275 kPa (40 psi). Each vehicle was driven, at walking speed, along a plot with one wheel running down the middle of the plot and the other outside of the plot. Nine passes of each vehicle were made in the plots. Four measurements of infiltration rate, soil bulk density and volumetric soil moisture content as described previously were made in each wheel path.

Table 1. Predevelopment infiltration tests on the natural wooded lots (n = 16 for each lot).

Lot	A	B	C	E
	Infiltration rate (mm hr^{-1})*			
Average	634	377	582	464
Maximum	1,023	764	881	862
Minimum	329	33	261	168
CV (%)	37.7	52.0	35.7	40.8

*25.4 mm hr^{-1} = 1 in hr^{-1}

Results and Discussion

Compaction due to construction. *Activities undisturbed infiltration rates.* Infiltration tests were conducted across soil moisture conditions ranging from five to 12 percent by volume. Particle size analysis of soil samples collected on site resulted in greater than 91 percent sand, less than seven percent silt, and less than two percent clay across all samples. There was no relationship between soil moisture and infiltration rate and the testing sites were all well-drained. The infiltration rates on the undisturbed wooded lots were generally very high with average rates varying from 377 to 634 mm hr^{-1} (14.8 to 25.0 inches hr^{-1}; Table 1). These values were in the range of values reported in the literature for similar conditions (Felton and Lull, 1963; Kays, 1980; Pitt et al., 1999). The infiltration rates measured in these wooded areas were highly variable. The maximum measured infiltration rate was 1,023 mm hr^{-1} (40.2 in hr^{-1}) and the minimum measured infiltration rate was 33 mm hr^{-1} (1.3 in hr^{-1}). Table 1 shows coefficient of variation between 35.7 percent and 52.0 percent across the measurements made on individual lots.

The average infiltration rates measured on the undisturbed natural wooded areas were greater than the 100-year, 24-hour design storm intensity of 254 mm hr^{-1} (10.0 in hr^{-1}) for this region in Florida (FDOT, 2003). The average infiltration rate on each lot varied from 2.5 times to 1.5 times greater than this design storm. This would indicate that, theoretically there would be no runoff from these lots for the 100-year, 24-hour design storm, and runoff would only occur if the groundwater table was to rise to the surface.

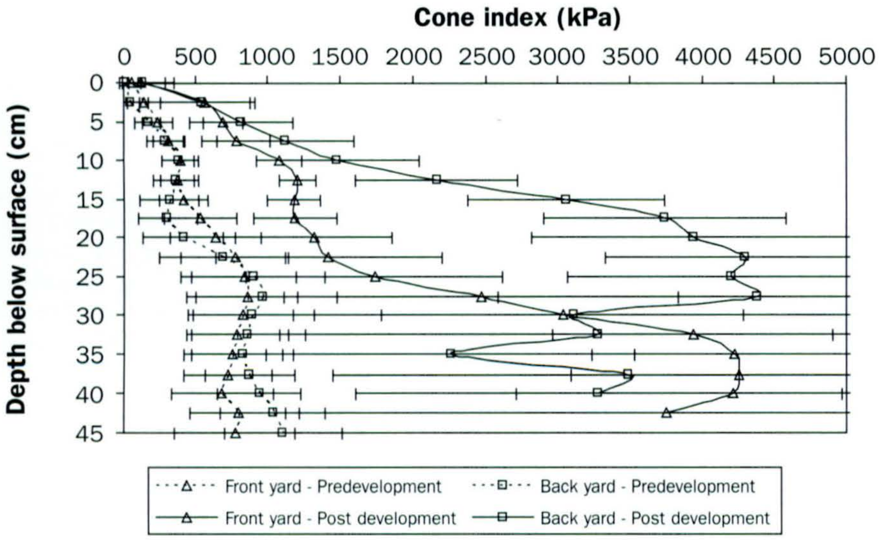
Post development infiltration rates. The post development infiltration measurements on lot A showed a reduction in infiltration rate from 861 mm hr^{-1} to 175 mm hr^{-1} (80 percent reduction) on the front yard and from 590 mm hr^{-1} to 8 mm hr^{-1} (99 percent reduction) on the backyard. The predevelopment infiltration rates were measured in approximately the same location as the post development infiltration rates. The front and back yard measurements for both the predevelopment conditions ($p = 0.037$) and post development conditions ($p = 0.026$) were statistically different. There were also significant differences between the infiltration rates for the predevelopment and post development conditions for both the front yard ($p = 0.004$) and back yard ($p = 0.007$).

Figure 1 shows predevelopment and post development mean cone index values measured on natural wooded site A. The predevelopment data for the front yard and back yard showed a maximum cone index of 858 kPa (124 psi) and 1,104 kPa (160 psi), respectively. The post development data for the front and back yard showed a maximum cone index of 4,260 kPa (620 psi) and 4,382 kPa (637 psi), respectively. This change in cone index during development of the lot was due to compaction that occurred during the construction process. The maximum cone index in the front yard occurred at 37.5 cm (14.8 in) deep while the maximum compaction on the back yard occurred at 27.5 cm (10.8 in) deep. The fill that was brought onto the front yard area, for grading purposes, resulted in this 10 cm (4.0 in) difference in depth of maximum cone index.

Side-by-side testing. Compaction from heavy construction equipment caused an overall decrease in the infiltration rate, from 733 to 178 mm hr^{-1} (28.9 to 7.0 in hr^{-1}) and a corresponding increase in bulk density, from 1.34 to 1.49 g/cm^3 (83.6 to 93.0 lb/ft^3; see Table 2). These overall changes are statistically significant for the infiltration results ($p < 0.001$) and for the overall bulk density results ($p = 0.001$). These data support the hypothesis that compaction caused by the vehicular traffic, during construction of urban developments, can result in a significantly increased bulk density and a significantly decreased infiltration rate.

Figure 1

Predevelopment and post development cone index values for natural wooded lot A, where error bars represent one standard deviation. Note that 1 inch = 2.54 cm and 1 psi = 6.89 kPa.



The natural wooded area was not subject to vehicle traffic. The planted forest would have been subjected to planting and harvesting activities involving heavy equipment that would have caused some compaction. The significant difference ($p = 0.008$) between the mean undisturbed infiltration rates on the natural wooded site (908 mm hr^{-1}; 35.7 in hr^{-1}) and the planted forest sites (631 mm hr^{-1}; 24.8 in hr^{-1}) was therefore expected; however, there was no significant difference between the undisturbed bulk densities ($p = 0.144$). The lack of a significant difference in bulk densities could be due to the soil core samples being collected in the top 10 cm (3.9 in) of the soil profile after clearing of the surface organic material. The effect of compaction is greatest at depths below 30 cm (11.8 in) (Hakansson and Petelkau, 1994); the soil samples collected in the top 10 cm (3.9 in) would not show this effect. Figure 2 shows the difference between average cone index value on the natural wooded lot and the planted forest lots. The greatest effect of compaction occurred between 25 cm (9.8 in) and 32.5 cm (12.8 in).

It is also interesting to note that after compaction there was no statistical difference ($p = 0.746$) in the infiltration rates and bulk densities measured on the natural wooded lot or those measured on the planted forest lots ($p = 0.563$). This indicates that although these sites had different undisturbed infiltration rates, compaction due to construction traffic resulted in no significant difference in infiltration rates.

From Figure 2 it should be noted that there was a difference between the magnitudes of the cone index graphs from the natural wooded lot and the planted forest lots. The natural wooded lot had maximum cone index values of 1,071 kPa (156 psi) and 1,965 kPa (286 psi) for undisturbed and disturbed area tests, respectively. On the planted forest lots, maximum cone index values were 1,914 to 3,741 kPa (279 to 545 psi) for the same respective testing conditions. This evidence supports the theory that the planted forest lot had undergone compaction in the past, which decreased the undisturbed infiltration rates compared to the natural wooded lot.

Effect of compaction level on infiltration rates. *Controlled compaction.* The results of the ANOVA conducted on infiltration rate and soil bulk density data (Figure 3), on both the pasture and wooded subplots showed that there was a significant difference between the non-compacted infiltration rates on the pasture (225 mm/hr; 8.9 inches/hr) and on the wooded area (487 mm hr^{-1}; 19.2 in hr^{-1}). However, the two locations had the same textural soil classifications (sand; 91 percent sand, less than nine percent silt, and less than four percent clay across all samples) and the same non-compacted mean bulk densities (1.49 g/cm^3; 93.0 lb/ft^3). There was no significant effect due to spatial variations in soil ($p>0.33$) within each experimental location. Statistically significant differences were not found between the mean infiltration rates of 65 mm hr^{-1} (2.6 in hr^{-1}), 30 mm hr^{-1} (1.2 in hr^{-1}) and 23 mm hr^{-1} (0.9 in hr^{-1}) that occurred after 30 second, three minutes, and 10 minutes of compaction on the pasture. This result suggests that compaction over the various levels imposed in this study did not substantially decrease the infiltration rate. Therefore, over the range of compaction that we considered, the soil was either compacted or non-compacted in terms of the effect on infiltration rate. A similar trend was observed with the data from the wooded site; however, a statistically significant difference was found between the 30-second treatment (79 mm hr^{-1}; 3.1 in hr^{-1}) and the 10-minute treatment (20 mm hr^{-1}; 0.8 in hr^{-1}).

The mean bulk densities after 10 minutes of compaction were significantly different

Table 2. Average infiltration rates, bulk density, coefficient of variation (in parentheses with units of percent) and paired t-test probability from natural wooded lot F, planted forest lots G and H (n = 6 for each lot and each compaction level except where noted).

	Mean infiltration rate (mm hr^{1})*			Bulk density (g/cm^3)†		
Lot	Undisturbed (%)	Compacted (%)	p value	Undisturbed (%)	Compacted (%)	p value
H‡	637 (22.7)	187 (52.4)	0.003	1.20 (17.2)	1.48 (5.0)	0.009
G	652 (26.9)	160 (52.0)	<0.001	1.40 (6.5)	1.52 (9.3)	0.110
F	908 (23.2)	188 (50.1)	0.001	1.42 (4.1)	1.47 (7.1)	0.252
Average	733 (28.8)	178 (49.1)	<0.001	1.34 (12.1)	1.49 (7.1)	0.001

*** 25.4 mm hr^{1} = 1 in hr^{1}**

† 1 g/cm^3 = 62.4 lb/ft^3

‡ n = 4 for compacted testing on this lot since two sites were destroyed due to land clearing.

Figure 2

Average cone index values (n = 6 for F and G; n = 4 for H) for undisturbed and compacted sites in naturally wooded areas and a planted forest, error bars represent one standard deviation. Note that 1 inch = 2.54 cm and 1 psi = 6.89 kPa.

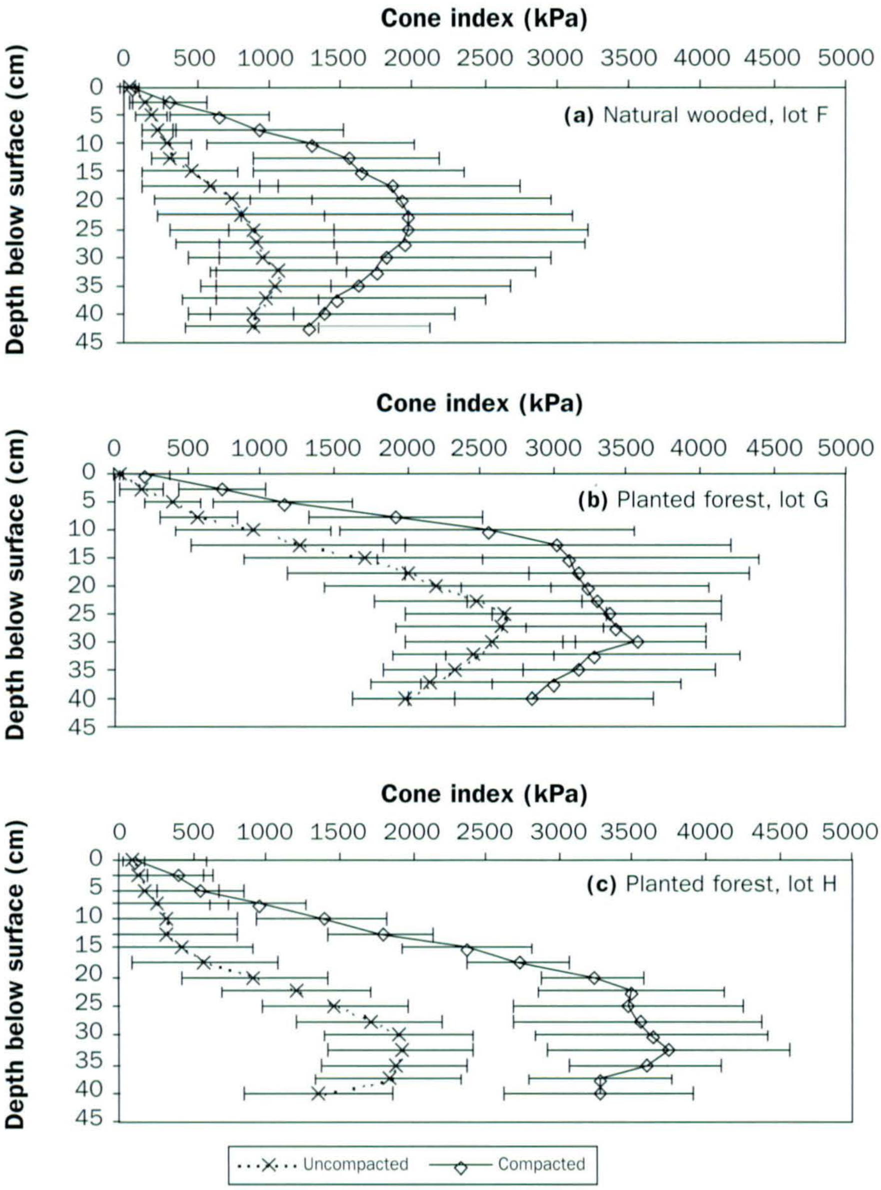


Table 3. Correlation and probability values (p) between average cone index (CI) at 2.5 cm depth increments and average surface infiltration rates, as measured on the compacted and undisturbed locations on natural wooded lot F, planted forest lot G and H.

Depth (cm)	Pearson correlation coef. (r)	p
0.0	-0.581	0.227
2.5	-0.757	0.081
5.0	-0.807	0.052
7.5	-0.804	0.054
10.0	-0.818	0.047
12.5	-0.826	0.043
15.0	-0.815	0.048
17.5	-0.817	0.047
20.0	-0.811	0.050
22.5	-0.785	0.064
25.0	-0.756	0.082
27.5	-0.753	0.084
30.0	-0.727	0.102
32.5	-0.705	0.118
35.0	-0.691	0.129
37.5	-0.675	0.141
40.0	-0.704	0.118

between the pasture and the wooded locations (Figure 3). This can be explained because the maximum Proctor density of 1.89 g/cm^3 (117.9 lb/ft^3) on the wooded site compared to the maximum Proctor density of 1.83 g/cm^3 (114.2 lb/ft^3) for the pasture, indicates that the wooded site can be compacted to a greater bulk density. The bulk density of the pasture soil after 10 minute of compaction was 1.73 g/cm^3 (108.0 lb/ft^3), this equates to approximately 95 percent of the maximum Proctor density and the bulk density of the soil at the wooded area after 10 minute of compaction was 1.79 g/cm^3 (111.7 lb/ft^3), which also equates to 95 percent of the maximum Proctor density.

The cone index throughout the profile on the non-compacted wooded area was lower than the cone index measured on the non-compacted pasture (Figure 4). The maximum average cone index on the non-compacted wooded subplots was 1,213 kPa (177 psi) at 42.5 cm (16.7 in) and the maximum average cone index on the non-compacted pasture subplots was 4,145 kPa (603 psi) at 37.5 cm (14.8 in). The pasture was subjected to compaction (caused by livestock and vehicles) in the past that probably contributed to the increased cone index. However, the difference in cone index between the pasture and the wooded site occurred at depths greater than the 10 cm (3.9 in) used for sampling bulk density. On the wooded sites, an increase in average cone index was negatively correlated with infiltration rate (Table 3). The strongest correlation occurred between 10 and 20 cm (3.9 and 7.9 in) depths ($p < 0.05$), further indicating that compaction occurs below 10 cm (3.9 in) depth.

Vehicular compaction. Table 4 summarizes the mean infiltration rates and bulk density data collected in the wheel ruts created during the vehicular compaction trial. The ANOVA indicated no significant difference between mean infiltration rates in the backhoe tracks and in the pickup tracks, although the backhoe tracks did show a numerically lower mean infiltration rate (59 mm hr^{-1}; 2.3 in hr^{-1}) than the pickup (68 mm hr^{-1}; 2.7 in hr^{-1}). Both the backhoe and pickup resulted in significantly higher mean infiltration rates than the dump truck (23 mm hr^{-1}; 0.9 in hr^{-1}).

There were no significant differences

Figure 3

Average infiltration rate and bulk density measurements (n = 4) from a pasture and naturally wooded site. Standard deviations are indicated by error bars, while means that are not significantly different (α = 0.05) are grouped by the same letter. T0, T0.5, T3 and T10 represent compaction treatments of 0, 0.5, 3 and 10 minutes with a portable compaction device, respectively. Note that 25.4 cm = 1 inch and 1 g/cm³ = 62.4 lb/ft³.

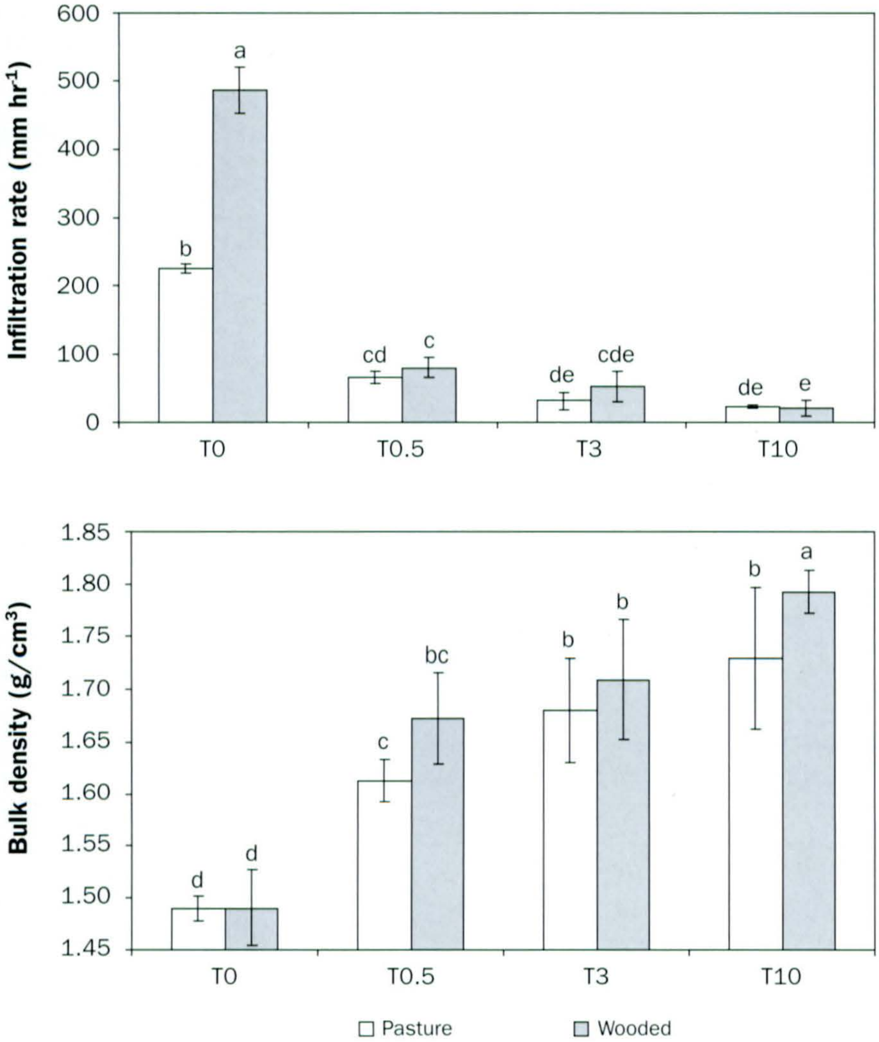


Table 4. Mean infiltration rate and bulk density result from tests conducted in the wheel ruts of a dump truck, backhoe and pickup after nine passes over a graded pasture. Means that were not significantly different were grouped with the same letter (n = 4 for each vehicle).

	Infiltration rate (mm hr^{-1})*	CV (%)‡	Bulk density (g/cm^3)†	CV (%)
Dump truck	23b	43.9	1.68a	2.3
Back hoe	59a	14.1	1.61a	1.9
Pickup	68a	23.1	1.61a	2.5

* **25.4 mm hr^{-1} = 1 inch hr^{-1}**

† **1 g/cm^3 = 62.4 lb/ft^3**

‡ **Coefficient of variation.**

between the mean bulk densities for the three treatments, although the dump truck did result in a numerically higher mean bulk density (1.68 g/cm^3; 104.8 lb/ft^3) than the backhoe and pickup (1.61 g/cm^3; 100.5 lb/ft^3). The lack of a significant difference between the mean bulk densities, again may be due to the bulk density being determined from soil samples collected in the top 10 cm (3.9 in) of the soil profile, since compaction tends to occur below 10 cm (3.9 in) as has been shown previously.

Summary and Conclusion

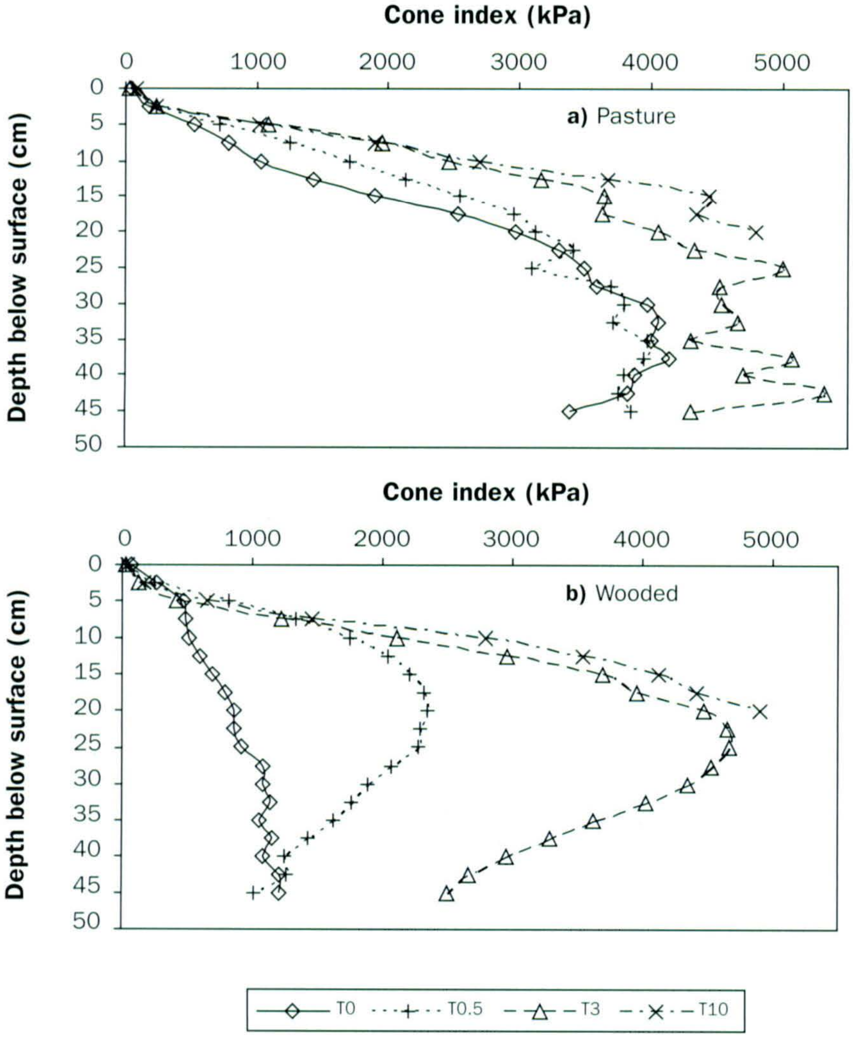
Soil compaction was shown to have a negative effect on infiltration rates of soils in north central Florida. On these sandy soils, the lowest level of compaction resulted in significantly lower infiltration rates; therefore, any amount of compaction must be avoided on these soils if runoff from development sites is to be minimized. However, it was shown that there could be a significant difference between the effect of compaction caused by relatively light construction equipment (i.e. a backhoe and pickup) and very heavy equipment (i.e. a fully loaded dump truck). For the purposes of determining potential infiltration rates, soils could be classified as either compacted or non-compacted. This classification of the compaction of a soil could have a significant affect on hydrological and stormwater modeling, particularly for low impact development projects where the soil infiltration rates are critical since infiltration is a key component of the stormwater network. Accurate infiltration rate information is also important in traditional runoff estimation from urban areas because undisturbed soil infiltration rates are typically assumed for pervious areas. Overestimation of the soil infiltration rate would result in an underestimation of the runoff from a specified area and a resultant underestimation of a flooding event.

To maintain predevelopment infiltration rates on a lot, areas of the development should be left undisturbed. Demarcating areas of the development to prevent compaction of the soil would help maintain predevelopment infiltration rates. Special efforts should also be made to leave natural areas, undisturbed as these areas were shown to have the highest infiltration rates. Reducing the use of any equipment on the lot as much as possible would also help limit the reduction in infiltration rates caused by compaction.

Measuring infiltration rates is a lengthy procedure compared to measuring cone index. Therefore, cone index could be used to quickly and efficiently identify areas of

Figure 4

Average cone index values for each level of compaction (n = 4) at the pasture and the wooded sites. T0, T0.5, T3 and T10 represent compaction treatments of 0, 0.5, 3 and 10 minutes with a portable compaction device, respectively. Note that 1 inch = 2.54 cm and 1 psi = 6.89 kPa.



a development that have been exposed to compaction and are thus contributing to decreased infiltration rates.

Acknowledgements

Special thanks are given to Danny Burch for his help in putting together the equipment needed for infiltration tests and Brent Addison for his help in conducting infiltration tests. This research was supported by the Florida Agricultural Experiment Station and a grant from St. Johns River Water Management District and approved for publication as Journal Series No. R-10532.

References Cited

American Society of Agricultural Engineers (ASAE). 2000. Soil cone penetrometer. ASAE Standards No. S313.3. American Society of Agricultural Engineers, St. Joseph, Michigan.

American Society of Testing and Materials (ASTM). 2002a. Standard test method for density of soil in place by the drive-cylinder method. Annual Book of ASTM Standards 04.08 No. D2937-00. American Society of Testing and Materials, West Conshohocken, Pennsylvania.

American Society of Testing and Materials (ASTM). 2002b. Standard test method for laboratory determination of water (Moisture) Content of soil and rock by mass. *In:* Annual Book of ASTM Standards 04.08. American Society of Testing and Materials, West Conshohocken, Pennsylvania.

American Society of Testing and Materials (ASTM). 2002c. Standard test methods for laboratory compaction characteristics of soil using standard effort [12,400 ft-lbf/ft^3 (600 kN-m/m^3)]. D698-00. Annual Book of ASTM Standards 04.08. American Society of Testing and Materials, West Conshohocken, Pennsylvania.

Blake, G.R. and J.H. Hartge. 1986. Bulk density. Pp. 363-375. *In:* Methods of soil analysis, Part I. ASA Monograph No. 9. American Agronomy Society, Madison, Wisconsin.

Buster, T.P. 1979. Soil survey of Marion County, Florida. Soil Conservation Service, Washington, D.C.

Carlisle, V.W., F. Sodek, M.E. Collins, L.C. Hammond, and W.G. Harris. 1989. Characterization data for selected Florida soils. Soil Science Research Report No. 89-1. University of Florida, Institute of Food and Agricultural Sciences, Gainesville, Florida.

Chow, V., D. Maidment, and L. Mays. 1988. Subsurface water. Pp. 109-110. *In:* Applied hydrology. McGraw-Hill, Inc., New York, New York.

Felton, P.M. and H.W. Lull. 1963. Suburban hydrology can improve watershed conditions. Pp. 93-94. *In:* Public Works No. 94.

Florida Department of Transportation (FDOT). 2003. Drainage manual. Florida Department of Transportation, Office of Design, drainage section, Tallahassee, Florida.

Gardner, W.H. 1986. Water content. Pp. 493-544. *In:* Methods of soil analysis, Part I. ASA Monograph No. 9. American Agronomy Society, Madison, Wisconsin.

Gee, G.W. and J.W. Bauder. 1986. Particle size analysis. Pp. 383-411. *In:* Methods of soil analysis, Part I. ASA Monograph No. 9. American Agronomy Society, Madison, Wisconsin.

Gregory, J.H., M.D. Dukes, G.L. Miller, and P.H. Jones. 2005. Analysis of double-ring infiltration techniques and development of a simple automatic water delivery system. Applied Turfgrass Science. Available at: http://www.plantmanagementnetwork.org/pub/ats/guide/2005/ring/.

Hakansson, I. and H. Petelkau. 1994. Benefits of limited axle load. Pp. 479-500. *In:* Soil compaction in crop production. Elsevier Science B.V., Amsterdam, Netherlands.

Hamilton, G.W. and D.V. Waddington. 1999. Infiltration rates on residential lawns in central Pennsylvania. Journal of Soil and Water Conservation 54(3):564-568.

Horton, R., M.D. Ankeny, and R.R. Allmaras. 1994. Effects of compaction on soil hydraulic properties. Pp. 479-500. *In:* Soil compaction in crop production. Elsevier Science B.V., Amsterdam, Netherlands.

Kays, B.L. 1980. Relationship of forest destruction and soil disturbance to increased flooding in the suburban North Carolina Piedmont. Pp. 118-1125. *In:* Metropolitan Tree Improvement Alliance Proceedings No. 3. Rutgers, New Jersey.

Kelling, K. and A. Peterson. 1975. Urban lawn infiltration rates and fertilizer runoff losses under simulated rainfall. Pp. 348-352. *In:* Soil Science Society of America Proceedings No. 39. Soil Science Society of America, Madison, Wisconsin.

Lal, R. and D.M. Vandoren. 1990. Influence of 25 years of continuous corn production by three tillage methods on water infiltration for two soils in Ohio. Soil and Tillage Research 16:71-84.

Pitt, R., R. Harrison, C. Henry, D. Xue, and T. O'Conner. 1999. Infiltration through disturbed urban soils and compost-amended soil effects on runoff quality and quantity. No. EPA/600/R-00/016. U.S. Environmental Protection Agency, Office of Research and Develop-ment, Washington, D.C.

Prince George's County. 1999. Low impact development design strategies: An integrated design approach. Maryland Department of Environmental Resource Programs and Planning Division, Largo, Maryland.

Richard, G., I. Cousin, J.F. Sillon, A. Bruand, and J. Gue'rif. 2001. Effect of compaction on soil porosity: Consequences on hydraulic properties. European Journal of Soil Science 52:49-58.

SAS. 2001. SAS User's Guide: Statistics. Version 8.02. SAS Institute, Inc. Cary, North Carolina.

U.S. Census Bureau. 2004. U.S. New privately owned housing units authorized by state: 2003. Manufacturing, Mining and Construction Statistics. Washington D.C.: U.S. Census Bureau. Available at: http://www.census.gov/const/www/03statepiechart.pdf. Accessed 4 June 2005.

U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS). 2000. Urban soil compaction. Urban Technical Note No. 2. U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Quality Institute, Auburn, Alabama.

U.S. Department of Agriculture Soil Conservation Service (USDA-SCS). 1985. Soil survey of Alachua County, Florida. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C.

Soil carbon pools in central Texas: Prairies, restored grasslands, and croplands

K.N. Potter and J.D. Derner

ABSTRACT: Establishment of perennial grasses on degraded soils has been suggested as a means to improve soil quality and sequester carbon in the soil. Particulate organic carbon may be an important component in the increased soil carbon content. We measured particulate organic carbon [defined as organic carbon in the 53 to 2000 μm (0.002 to 0.08 in) size fraction] and mineral associated organic carbon (defined as the less than 53 μm (0.002 in) size fraction) at three locations in central Texas. Each location had a never-tilled native grassland site, a long-term agricultural site and a restored grassland on a previously tilled site. Organic carbon pool sizes varied in the surface 40 cm (16 in) of native grassland, restored grasslands and agricultural soils. The native grasslands contained the largest amounts of total organic carbon, while the restored grasslands and agricultural soils contained similar amounts of total organic carbon. Both particulate organic carbon and mineral associated carbon pools were reduced beyond the depth of tillage in the restored grass and agricultural soils compared to the native grassland soils. The restored grassland soils had a larger particulate organic carbon content than the agricultural soils, but the increase in particulate organic carbon was limited to the surface 5 cm (2 in) of soil. Trends in particulate organic carbon accumulation over time from nine to 30 years were not significant in this study.

Keywords: Particulate organic carbon (POC), native grassland, soil quality, mineral associated carbon (MAC), total organic carbon (TOC)

Soil organic matter is a heterogeneous mixture of organic substances that has an important role in determining soil productivity. For modeling purposes, it has been beneficial to separate soil organic matter into separate pools that have different functions and degradation rates in the soil. However, in practice, it has been difficult to separate soil organic matter into pools similar to the conceptual pools proposed by the modeling community. Techniques developed to isolate soil organic matter pools include chemical, densiometry, and size fractionation methods. Cambardella and Elliott (1992) developed a technique based upon size fractionation that isolates the organic size fraction between 52 to 2000 μm (0.002 to 0.08 in), which they called particulate organic matter. The particulate organic matter pool has been related to nutrient mineralization (N, Parry et al., 2000; and P, Salas et al., 2003), vegetation type (forest, Barrios et al., 1997; and crop, Bremer et al., 1995), soil carbon content under various tillage practices (Needelman et al., 1999; Wander and Bidart, 2000), and soil quality changes (Franzluebbers and Arshad, 1997; Wander et al., 1998; Chan, 1997).

The particulate organic matter fraction, of which the carbon content is referred to as the particulate organic carbon, appears to be more sensitive to changes in management practices than total organic carbon (Cambardella and Elliott, 1992; Needelman et al., 1999; Wander and Bidart, 2000; Bowman et al., 1999). Particulate organic carbon content often changes more rapidly than the total organic carbon content with a change in management. This difference may be a result of differential decomposition rates under various management and climatic conditions

Ken Potter is soil scientist with the U.S. Department of Agriculture Grassland, Soil, and Water Research Laboratory in Temple, Texas. **Justin D. Derner** is a rangeland scientist with the U.S. Department of Agriculture, High Plains Grassland Research Station in Cheyenne, Wyoming.

PHYSIOLOGICAL ECOLOGY

A Series of Monographs, Texts, and Treatises

EDITED BY

T. T. KOZLOWSKI

University of Wisconsin
Madison, Wisconsin

T. T. KOZLOWSKI. Growth and Development of Trees, Volumes I and II – 1971

DANIEL HILLEL. Soil and Water: Physical Principles and Processes, 1971

J. LEVITT. Responses of Plants to Environmental Stresses, 1972

V. B. YOUNGNER AND C. M. MCKELL (Eds.). The Biology and Utilization of Grasses, 1972

T. T. KOZLOWSKI (Ed.). Seed Biology, Volumes I, II, and III – 1972

YOAV WAISEL. Biology of Halophytes, 1972

G. C. MARKS AND T. T. KOZLOWSKI (Eds.). Ectomycorrhizae: Their Ecology and Physiology, 1973

T. T. KOZLOWSKI (Ed.). Shedding of Plant Parts, 1973

ELROY L. RICE. Allelopathy, 1974

T. T. KOZLOWSKI AND C. E. AHLGREN (Eds.). Fire and Ecosystems, 1974

J. BRIAN MUDD AND T. T. KOZLOWSKI (Eds.). Responses of Plants to Air Pollution, 1975

REXFORD DAUBENMIRE, Plant Geography, 1978

Soil and Water

Physical Principles and Processes

DANIEL HILLEL

DEPARTMENT OF SOIL SCIENCE
THE HEBREW UNIVERSITY OF JERUSALEM
REHOVOT, ISRAEL

ACADEMIC PRESS New York San Francisco London

A Subsidiary of Harcourt Brace Jovanovich, Publishers

'his is a second-order partial differential equation of the elliptical type, and t can be solved in certain cases to obtain a quantitative description of water low in various systems.

In general, a differential equation can have an infinite number of solutions. Γo determine the specific solution in any given case, it is necessary to specify he *boundary conditions*, and, in the case of unsteady flow, of the *initial conditions* as well. Various types of boundary conditions can exist (e.g., impervious boundaries, free water surfaces, boundaries of known pressure, or known inflow or outflow rates, etc.), but in each case the flux and pressure head must be continuous throughout the system. In layered soils, the hydraulic conductivity and water content may be discontinuous across interlayer boundaries (that is, they may exhibit abrupt changes). Flow equations for inhomogeneous, anisotropic, and compressible systems were given by Bear *et al.* (1968).

Philip (1969) recently analyzed flow in swelling (compressible) media. In unsteady flow, the solid matrix of a swelling soil undergoes motion, so that Darcy's law applies to water movement relative to the particles, rather than relative to physical space. Experimental work with such soils was carried out by Smiles and Rosenthal (1968).

M. Summary

A proper physical description of water flow in the soil requires that three parameters be specified: flux, hydraulic gradient, and conductivity. Knowledge of any two of these allows the calculation of the third, according to Darcy's law. This law states that the flux equals the product of conductivity by the hydraulic gradient. The hydraulic gradient itself includes both the pressure and the gravitational potential gradients, the first of which is the exclusive cause of flow in a horizontal system, while the second occurs in vertical systems. The hydraulic conductivity at saturation is a characteristic property of a soil toward water flow, and it is related to porosity and pore-size distribution.

5 *Flow of Water in Unsaturated Soil*

A. General

Most of the processes involving soil-water flow in the field, and in the rooting zone of most plant habitats, occur while the soil is in an unsaturated condition. Unsaturated flow processes are in general complicated and difficult to describe quantitatively, since they often entail changes in the state and content of soil water during flow. Such changes involve complex relations among the variable water content (wetness), suction, and conductivity, which may be affected by hysteresis. The formulation and solution of unsaturated flow problems very often require the use of indirect methods of analysis, based on approximations or numerical techniques. For this reason, the development of rigorous theory and methods for treating these problems was rather late in coming. In recent years, however, unsaturated flow has become one of the most important and active topics of research in soil physics, and this research has resulted in significant theoretical and practical advances.

B. Comparison of Unsaturated vs. Saturated Flow

In the previous chapter, we stated that soil-water flow is caused by a driving force resulting from an effective potential gradient, that flow takes place in the direction of decreasing potential, and that the rate of flow (flux) is proportional to the potential gradient and is affected by the geometric properties of the pore channels through which flow takes place. These principles apply in unsaturated, as well as in saturated soils.

The moving force in a saturated soil is the gradient of a positive pressure potential.[1] On the other hand, water in an unsaturated soil is subject to a subatmospheric pressure, or suction, and the gradient of this suction likewise constitutes a moving force. The matric suction is due, as we have pointed out, to the physical affinity of the water to the soil-particle surfaces and capillary pores. Water tends to be drawn from a zone where the hydration envelopes surrounding the particles are thicker, to where they are thinner, and from a zone where the capillary menisci are less curved to where they are more highly curved.[2] In other words, water tends to flow from where suction is low to where it is high. When suction is uniform all along a horizontal column, that column is at equilibrium and there is no moving force. Not so when a suction gradient exists. In that case, water will flow in the pores which remain water-filled at the existing suction, and will creep along the hydration films over the particle surfaces, in a tendency to equilibrate the potential.

The moving force is greatest at the "wetting front" zone of water entry into an originally dry soil (see Fig. 5.2). In this zone, the suction gradient can be many bars per centimeter of soil. Such a gradient constitutes a moving force thousands of times greater than the gravitational force. As we shall see later on, such strong forces are sometimes required (for a given flux) in view of the extremely low hydraulic conductivity which a relatively dry soil may exhibit.

The most important difference between unsaturated and saturated flow is in the hydraulic conductivity. When the soil is saturated, all of the pores are filled and conducting, so that conductivity is maximal. When the soil becomes unsaturated, some of the pores become airfilled and the conductive portion of the soil's cross-sectional area decreases correspondingly. Furthermore, as suction develops, the first pores to empty are the largest ones, which

[1] We shall disregard, for the moment, the gravitational force, which is completely unaffected by the saturation or unsaturation of the soil.

[2] The question of how water-to-air interfaces behave in a conducting porous medium that is unsaturated is imperfectly understood. It is generally assumed, at least implicitly, that these interfaces, or menisci, are anchored rigidly to the solid matrix so that, as far as the flowing water is concerned, air-filled pores are like solid particles. The presence of organic surfactants which adsorb to these surfaces is considered to increase their rigidity or viscosity. Even if the air–water interfaces are not entirely stationary, however, the drag, or momentum transfer, between flowing water and air appears to be very small. The influence of the surface viscosity of air–water interfaces on the rheological behavior of soil water has not been evaluated (Philip, 1970). Preliminary experimental findings by E. E. Miller and D. Hillel suggest that a drag effect does occur, but that its magnitude is negligible for most practical purposes.

are the most conductive,[3] thus leaving water to flow only in the smaller pores. The empty pores must be circumvented, so that, with desaturation, the tortuosity increases. In coarse-textured soils, water sometimes remains almost entirely in capillary wedges at the contact points of the particles, thus forming separate and discontinuous pockets of water. In aggregated soils, too, the large interaggregate spaces which confer high conductivity at saturation become (when emptied) barriers to liquid flow from one aggregate to its neighbors.

For these reasons, the transition from saturation to unsaturation generally entails a steep drop in hydraulic conductivity, which may decrease by several orders of magnitude (sometimes down to 1/100,000 of its value at saturation) as suction increases from zero to one bar. At still higher suctions, or lower water contents, the conductivity may be so low[4] that very steep suction gradients, or very long times, are required for any appreciable flow to occur.

At saturation, the most conductive soils are those in which large and continuous pores constitute most of the overall pore volume, while the least conductive are the soils in which the pore volume consists of numerous micropores. Thus, as is well known, a sandy soil conducts water more rapidly than a clayey soil. However, the very opposite may be true when the soils are unsaturated. In a soil with large pores, these pores quickly empty and become nonconductive as suction develops, thus steeply decreasing the initially high conductivity. In a soil with small pores, on the other hand, many of the pores remain full and conductive even at appreciable suction, so that the hydraulic conductivity does not decrease as steeply and may actually be greater than that of a soil with large pores subjected to the same suction.

Since in the field the soil is unsaturated most of the time, it often happens that flow is more appreciable and persists longer in clayey than in sandy soils. For this reason, the occurrence of a layer of sand in a fine-textured profile, far from enhancing flow, may actually impede unsaturated water movement until water accumulates above the sand and suction decreases sufficiently for water to enter the large pores of the sand. This simple principle is all too often misunderstood.

[3] By Poiseuille's law, the total flow rate of water through a capillary tube is proportional to the fourth power of the radius, while the flow rate per unit cross-sectional area of the tube is proportional to the square of the radius. A 1-mm-radius pore will thus conduct as 10,000 pores of radius 0.1 mm.

[4] As very high suctions develop, there may (in addition to the increase in tortuosity and the decrease in number and sizes of the conducting pores) also be a change in the viscosity of the (mainly adsorbed) water, tending to further reduce the conductivity. (Miller and Low, 1963).

$$I = L_f \, \Delta\theta \tag{6.18}$$

(In the special case where θ_t is saturation and θ_i is zero, $I = fL_f$, where f is the porosity.) Therefore,

$$\frac{dI}{dt} = \Delta\theta \frac{dL_f}{dt} = K\frac{\Delta H_p}{L_f} = K\frac{\Delta\theta \cdot \Delta H_p}{I} \tag{6.19}$$

where dL_f/dt is the rate of advance of the wetting front. The infiltration rate is thus seen to be inversely related to the cumulative infiltration. Rearranging Eq. (6.19), we obtain:

$$L_f \, dL_f = K\frac{\Delta H_p}{\Delta\theta}\, dt = \tilde{D}\, dt \tag{6.20}$$

where the composite term $(K\,\Delta H_p/\Delta\theta)$ can be regarded as an effective diffusivity $\tilde{D}$ for the infiltrating profile. Integration gives

$$\frac{L_f^{\,2}}{2} = K\frac{\Delta H_p}{\Delta\theta}\, t = \tilde{D}t \tag{6.21}$$

$$L_f = \sqrt{2Kt\,\Delta H_p/\Delta\theta} = \sqrt{2\tilde{D}t} \tag{6.22}$$

or

$$I = \Delta\theta\sqrt{2\tilde{D}t}, \qquad i = \Delta\theta\sqrt{\tilde{D}/2t} \tag{6.23}$$

which compares with Eqs. (6.4) and (6.5) (the difference being in the $\sqrt{2\pi}$ ratio for the weighting of $\bar{D}$ vs. $\tilde{D}$, both being approximate[7]). Thus the depth of the wetting front is proportional to $\sqrt{t}$, and the infiltration rate is proportional to $1/\sqrt{t}$.

With gravity taken into account, the Green and Ampt approach gives

$$\frac{dI}{dt} = \Delta\theta \frac{dL_f}{dt} = K\frac{H_0 - H_f + L_f}{L_f} \tag{6.24}$$

which integrates to

$$\frac{Kt}{\Delta\theta} = L_f - (H_0 - H_f)\ln\left(1 + \frac{L_f}{H_0 - H_f}\right) \tag{6.25}$$

As t increases, the second term on the right-hand side of Eq. (6.25) increases more and more slowly in relation to the increase in L_f, so that, at very large times, we can approximate the relationship by

[7] $\tilde{D}$ can be regarded as an indication of what wetting-front value must be assumed for the Green and Ampt approach to work.

$$L_f \cong \frac{Kt}{\Delta\theta} + \delta \tag{6.26}$$

or

$$I \cong Kt + \delta$$

where δ can eventually be regarded as a constant.

The Green and Ampt relationships are essentially empirical, since the value of the effective wetting-front suction must be found by experiment. For infiltration into initially dry soil, it may be of the order of -50 to -100 cm H_2O, or ~ -0.1 bar (Green and Ampt, 1911; Hillel and Gardner, 1970). However, in actual field conditions, particularly where the initial moisture is not uniform, H_f may be undefinable. In many real situations, the wetting front is too diffuse to indicate its exact location at any particular time.

G. Infiltration into Layered Soils

The effect of profile stratification on infiltration was studied by Hanks and Bowers (1962),[8] who used a numerical technique for analyzing the flow equation, and by Miller and Gardner (1962), who conducted experiments on the effect of thin layers sandwiched into otherwise uniform profiles. A conducting soil must have continuous matric suction and hydraulic-head values throughout its length, regardless of layering sequence. However, the wetness and conductivity values may exhibit abrupt discontinuities at the interlayer boundaries.

One typical situation is that of a coarse layer of higher saturated hydraulic conductivity, overlying a finer-textured layer. In such a case, the infiltration rate is at first controlled by the coarse layer, but when the wetting front reaches and penetrates into the finer-textured layer, the infiltration rate can be expected to drop and tend to that of the finer soil alone. Thus, in the long run, it is the layer of lesser conductivity which controls the process. If infiltration continues for long, then positive pressure heads (a "perched water table") can develop in the coarse soil, just above its boundary with the impeding finer layer.

In the opposite case of infiltration into a profile with a fine-textured layer over a coarse-textured one, the initial infiltration rate is again determined by the upper layer. As water reaches the interface with the coarse lower layer, however, the infiltration rate may decrease. Water at the wetting front is normally under suction, and this suction may be too high to permit entry into the relatively large pores of the coarse layer. This explains the observation

[8] This technique was used by Green *et al.* (1962) to estimate infiltration in the field.

(Miller and Gardner, 1962) that the wetting-front advance stops for a time (though infiltration at the surface does not stop) until the pressure head at the interface builds up sufficiently to penetrate into the coarse material. Thus, a layer of sand or gravel in a medium or fine-textured soil, far from enhancing water movement in the profile, may actually impede it. The lower layer, in any case, cannot become saturated, since the restricted rate of flow through the less permeable upper layer cannot sustain flow at the saturated hydraulic conductivity of the coarse lower layer (except when the externally applied pressure, i.e., the ponding depth, is large).

The steady-state downflow of water through a two-layer profile into a free-water table beneath was analyzed by Takagi (1960). Where the upper layer is less pervious than the lower, negative pressures (suctions) were shown to develop in the lower layer, and these can remain constant throughout a considerable depth range.

H. Infiltration into Crust-Topped Soils

A very important special case of a layered soil is that of an otherwise uniform profile which develops a crust, or seal, at the surface. Such a seal can develop under the beating action of raindrops (Ekern, 1950; McIntyre, 1958; Tackett and Pearson, 1965), or as a result of the spontaneous slaking and breakdown of soil aggregates during wetting (Hillel, 1960). Surface crusts are characterized by greater density, finer pores, and lower saturated conductivity than the underlying soil. Once formed, a surface crust can greatly impede water intake by the soil (Fig. 6.6), even if the crust is quite

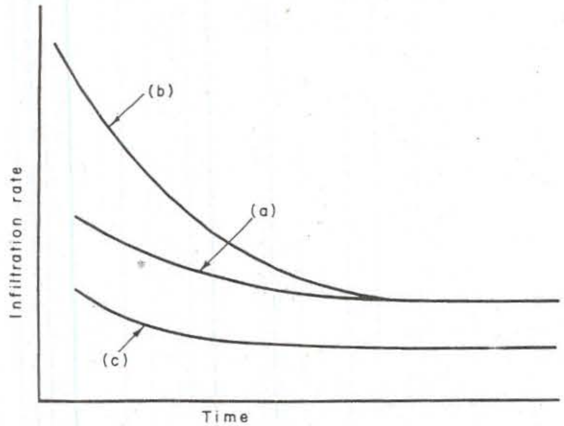


Fig. 6.6. Infiltrability as a function of time: (a) in a uniform soil; (b) in a soil with a more porous upper layer; and (c) in a soil covered by a surface crust.

thin (say, not more than several millimeters in thickness) and the soil is otherwise highly permeable. Failure to account for the formation of a crust can result in gross overestimation of infiltration.

An analysis of the effect of a developing surface crust upon infiltration was carried out by Edwards and Larson (1969), who adapted the Hanks and Bowers (1962) numerical solution to this problem. Hillel (1964), and Hillel and Gardner (1969, 1970) used a quasianalytical approach to calculate fluxes during steady and transient infiltration into crust-capped profiles from knowledge of the basic hydraulic properties of the crust and of the underlying soil.

The problem is relatively simple in the case of steady infiltration. Steady-state conditions require that the flux through the crust q_c be equal to the flux through the subcrust "transmission zone" q_u:

$$q_c = q_u$$

or

$$K_c\left(\frac{dH}{dz}\right)_c = K_u\left(\frac{dH}{dz}\right)_u \tag{6.27}$$

where K_c, $(dH/dz)_c$, K_u, and $(dH/dz)_u$ refer to the hydraulic conductivity and hydraulic-head gradient of the crust and underlying transmission zone, respectively. The gradient through the transmission zone tends to unity when steady infiltration is approached, as the suction gradient decreases with the increase in wetting depth, eventually leaving the gravitational gradient as the only effective driving force. In the absence of a suction-head gradient in the zone below the crust, we obtain (with the soil surface as our reference level)

$$q = K_u(\psi_u) = K_c\,\frac{H_0 + \psi_u + z_c}{z_c} \tag{6.28}$$

where $K_u(\psi_u)$ is the unsaturated hydraulic conductivity of the subcrust zone, a function of the suction head ψ_u which develops in this zone, beginning just under the hydraulically impeding crust; H_0 is the positive hydraulic head imposed on the surface by the ponded water; and z_c is the vertical thickness of the crust.

Where the ponding depth H_0 is negligible and the crust itself is very thin and of low conductivity (e.g., where z_c is very small in relation to the suction ψ_u which forms at the subcrust interface), we can assume the approximation

$$q_u = q_c = K_c\,\frac{\psi_u}{z_c} \tag{6.29}$$

The condition that the crust remain saturated even while its lower part will be under suction is that its critical air-entry ψ_a not be exceeded (i.e., $\psi_u < \psi_a$).

This, together with the condition that the subcrust hydraulic-head gradient approximate unity, leads to the approximation

$$\frac{K_u}{\psi_u} = \frac{K_c}{z_c} = \frac{1}{R_c} \tag{6.30}$$

i.e., the ratio of the hydraulic conductivity of the underlying soil transmission zone to its suction is approximately equal to the ratio of the crust's (saturated) hydraulic conductivity to its thickness. The latter ratio is the reciprocal of the hydraulic resistance per unit area of the crust R_c.[9] Also, by Eq. (6.28),

$$q = K_u(\psi_u) = \psi_u / R_c \tag{6.31}$$

Where the unsaturated conductivity of the underlying soil bears a known single-valued relation to the suction, it should be possible to calculate the steady infiltration rate and the suction in the subcrust zone on the basis of the measurable hydraulic resistance of the crust. Where the relation of matric suction to water content is also known, it should be possible to infer the subcrust water content during steady infiltration.

Employing a K vs. ψ relationship of the type $K = a\psi^{-n}$ (where a, and n are characteristic constants of the soil), Hillel and Gardner (1969) obtained the following[10]:

$$q = \frac{a^{1/(n+1)}}{R_c^{\,n/(n+1)}} = \frac{B}{R_c^{\,n/(n+1)}} \tag{6.32}$$

$$\psi_u = (aR_c)^{1/(n+1)} = BR_c^{\,1/(n+1)} \tag{6.33}$$

where $B = a^{1/(n+1)}$ is a property of the subcrust soil. The theoretical consequences of Eqs. (6.32) and (6.33) are illustrated in Fig. 6.7. These equations indicate how the infiltration rate decreases, and the subcrust suction increases, with increasing hydraulic resistance of the crust. Gardner (1956) has shown that the values of a and of n generally increase with increasing coarseness, textural as well as structural, of the soil. Sands may have n values of four or more, whereas clayey soils may have n values of about two. Tillage may pulverize and loosen the soil, thus increasing n, whereas compaction may have the opposite effect.

Both the crust and the underlying soil are seen to affect the infiltration rate and suction profile, and the crust-capped soil is thus viewed as a self-adjusting system in which the physical properties of the crust and underlying

[9] A distinction is made between the hydraulic resistance per unit area, defined as above, and the hydraulic resistivity, the latter being equal to the reciprocal of the conductivity.

[10] The relation of conductivity to suction does not always obey so simple an equation as $K = a\psi^{-n}$. An alternative expression, proposed by Hillel and Gardner (1969), may have more general validity: $K = K_s(\psi_a/\psi)^n$, for $\psi > \psi_a$.

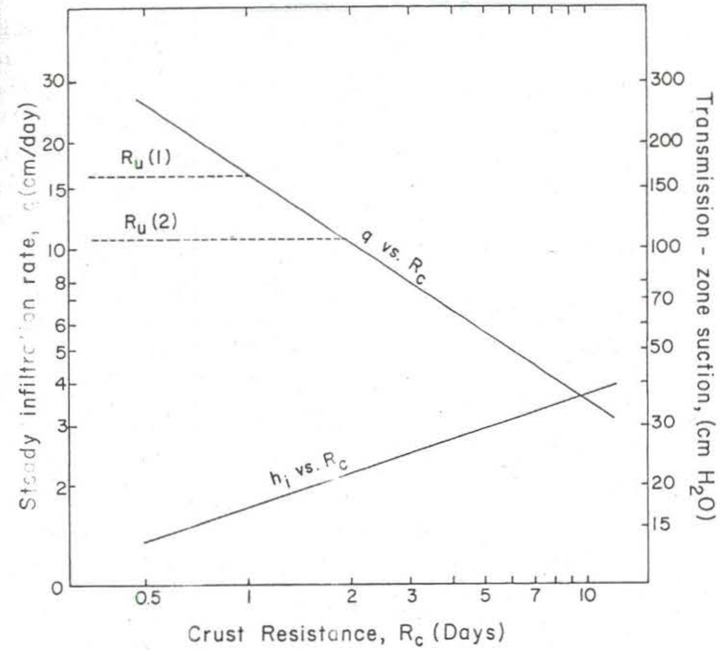


Fig. 6.7. Theoretical effect of crust resistance upon flux and subcrust suction during steady infiltration into crust-capped columns of a uniform soil with $n = 2$, $a = 4.9 \times 10^3$. The broken lines (1) and (2) indicate the hypothetical effect of subcrust hydraulic resistance R_u: $R_u(1) < R_u(2)$. The decreasing q vs. R_c curve applies only where the hydraulic conductance of the subcrust layers is not limiting. (After Hillel and Gardner, 1969.)

soil interact in time to form a steady infiltration rate and moisture profile. In this steadily infiltrating profile the subcrust suction which develops is such as to create a gradient through the crust and a conductivity in the subcrust zone which will result in an equal flux through both layers.

The problem is rather more complicated in the prevalent case of transient infiltration into an initially unsaturated profile, during which the flux, the wetting depth, the subcrust suction, and the conductivity might all be changing with time.

Assuming the Green and Ampt conditions (Section 6F), and with H_0 negligible, Hillel and Gardner (1970) recognized three stages during transient infiltration into crusted profiles: an initial stage, in which the rate is finite and dependent on crust resistance R_c and on an effective subsoil suction; an intermediate stage, in which cumulative infiltration I increases approximately as the square root of time; and a later stage, in which I can be expressed as the sum of a steady and a transient term, the latter becoming negligible at long times. I was shown to decrease with increasing R_c, particularly in coarse-textured and coarse-structured soils. Experimental data indicate that the cumulative infiltration curves of crusted profiles scale as the square root of their transmission-zone diffusivities. Thus, infiltration into a crusted profile can be described by the approximation that water enters into the subcrust soil at a nearly constant suction, the magnitude of which is determined by crust resistance and hydraulic characteristics of the soil.

Where the gravity effect is negligible (e.g., in horizontal flow or during the initial stages of vertical infiltration into an initially dry medium of high matric suction), the infiltration vs. time relationship was given by:

$$I = \sqrt{K_u^2 R_c^2 (\Delta\theta)^2 + 2K_u H_f \,\Delta\theta\, t} - K_u R_c \tag{6.34}$$

Where the gravity effect is significant, the expression given is

$$L_f = \frac{K_u t}{\Delta\theta} + (H_f - K_u R_c) \ln\left[\frac{H_f + (K_u t/\Delta\theta) + \delta(t)}{H_f}\right] \tag{6.35}$$

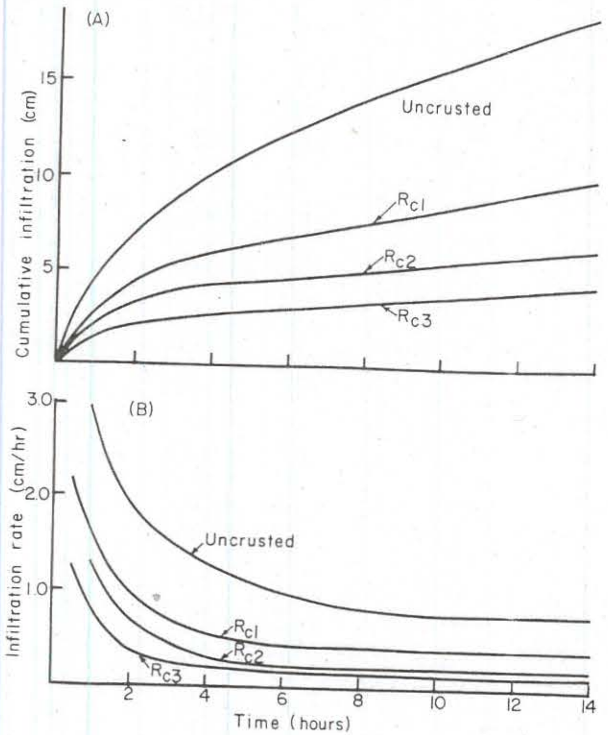


Fig. 6.8. Time dependence of cumulative infiltration (A) and of infiltration rate (B) for uncrusted and crusted columns of Negev loess. Crust resistance values R_{c1}, R_{c2}, R_{c3} are 3.2, 9.1, and 17 days, respectively (after Hillel and Gardner, 1969).

where the correction term $\delta(t)$ becomes negligibly small as t increases. Thus, L_f can be expressed as the sum of a steady and a transient term. Some experimental results are shown in Fig. 6.8.

I. Rain Infiltration

When rain or sprinkling intensity exceeds soil infiltrability, the infiltration process is the same as in the case of shallow ponding. If rain intensity is less than the initial infiltrability value of the soil, but greater than the final value, then at first the soil will absorb water at less than its potential rate and flow in the soil will occur under unsaturated conditions; however, if the rain is continued at the same intensity, and as soil infiltrability decreases, the soil surface will eventually become saturated and henceforth the process will continue as in the case of ponding infiltration. On the other hand, if rain intensity is at all times lower than soil infiltrability (i.e., lower than the saturated hydraulic conductivity), the soil will continue to absorb the water as fast as it is applied without ever reaching saturation. After a long time, as the suction gradients become negligible, the wetted profile will attain a wetness for which the conductivity is equal to the water application rate, and the lower this rate, the lower the degree of saturation of the infiltrating profile. This effect is illustrated in Fig. 6.9.

The process of infiltration under rain or sprinkler irrigation was studied by Youngs (1960) and by Rubin and Steinhardt (1963, 1963), Rubin *et al.* (1964), and Rubin (1966). The latter author, who used a numerical solution of the flow equation for conditions pertinent to this problem, recognized three modes of infiltration due to rainfall: (1) *nonponding infiltration*, involving rain not intense enough to produce ponding; (2) *preponding infiltration*, due to rain that can produce ponding but that has not yet done so; and (3) *rainpond infiltration*, characterized by the presence of ponded water. Rainpond infiltration is usually preceded by preponding infiltration, the transition between the two being called *incipient ponding*. Thus, nonponding and preponding infiltration are *rain-intensity-controlled* (or *flux-controlled*), whereas rainpond infiltration is controlled by the pressure (or depth) of water above the soil surface, as well as by the suction conditions and conductivity relations of the soil. Where the pressure at the surface is small, rainpond infiltration, like ponding infiltration in general, is *profile-controlled.*

In the analysis of rainpond or ponding infiltration, the surface boundary condition generally assumed is that of a constant pressure at the surface, whereas in the analysis of nonponding and preponding infiltration, the water flux through the surface is considered to be constant, or increasing. In actual field conditions, rain intensity might increase and decrease alternately, at times exceeding the soil's saturated conductivity (and its infiltrability) and

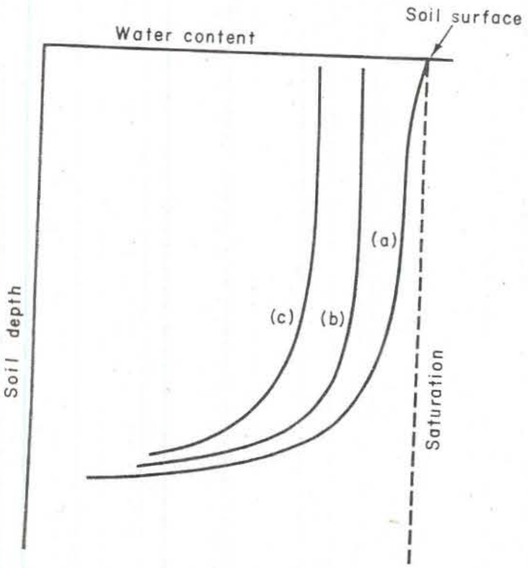


Fig. 6.9. The water-content distribution profile during infiltration: (a) under ponding; (b) under sprinkling at relatively high intensity; and (c) under sprinkling at a very low intensity.

at other times dropping below it. However, since periods of decreasing rain intensity involve complicated hysteresis phenomena, the analysis of composite rainstorms is very difficult and has not yet been carried out satisfactorily.

Rubin's analysis is based on the assumption of no hysteresis. The falling raindrops are taken to be so small and numerous that rain may be treated as a continuous body of "thin" water reaching the soil surface at a given rate. Soil air is regarded as a continuous phase, at atmospheric pressure. The soil is assumed to be uniform and stable (i.e., no fabric changes such as surface crusting).

We shall briefly review the consequences of Rubin's analysis in qualitative terms. If a constant pressure head is maintained at the soil surface (as in rainpond infiltration), then the flux of water into this surface must be constantly decreasing with time. If a constant flux is maintained at the soil surface, then the pressure head at this surface must be constantly increasing with time. Infiltration of constant-intensity rain can result in ponding only if the *relative rain intensity* (i.e., the ratio of rain intensity to the saturated hydraulic conductivity of the soil) exceeds unity. During nonponding infiltration under a constant rain intensity q_r, the surface suction will tend to a limiting value ψ_{lim} such that $K(\psi_{\text{lim}}) = q_r$.

Under rainpond infiltration, the wetted profile consists of two parts: an upper, water-saturated part; and a lower, unsaturated part. The depth of

the saturated zone continuously increases with time. Simultaneously, the steepness of the moisture gradient at the lower boundary of the saturated zone (i.e., at the wetting zone and the wetting front) is continuously decreasing (these phenomena accord with those of infiltration processes under ponding, as described in the previous sections of this chapter). The higher the rain intensity is, the shallower is the saturated layer at incipient ponding and the steeper is the moisture gradient in the wetting zone.

Figure 6.10 describes infiltration rates into a sandy soil during preponding

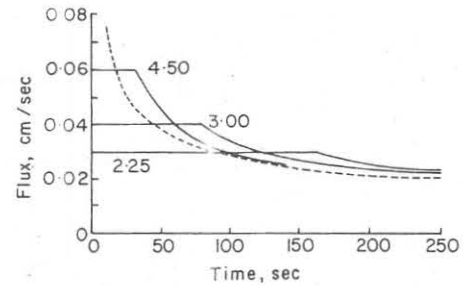


Fig. 6.10. Relation between surface flux and time during infiltration into Rehovot sand due to rainfall (solid lines) and flooding (dashed line). The numbers labeling the curves indicate the magnitude of the relative rain intensity (after Rubin, 1966).

and rainpond infiltration under three rain intensities. The horizontal parts of the curves correspond to preponding infiltration, and the descending parts to rainpond infiltration periods. As pointed out by Rubin (1966), the rainpond infiltration curves are of the same general shape and approach the same limiting infiltration rate, but they do not constitute horizontally displaced parts of a single curve, and do not coincide with the infiltration rate under flooding, which is shown as a broken line in the same graph.

The process of rain infiltration has not yet been studied in sufficient detail in the field to establish the applicability of existing theories. Complications due to the discreteness of raindrops (which causes alternate saturation and redistribution at the surface), as well as to the highly variable nature of rainstorm intensities and raindrop energies, and the unstable nature of many (perhaps even most) soils, can cause anomalies disregarded by idealized theories. Additional complications can arise in cases of air occlusion and when the soil exhibits profile or areal heterogeneity.

J. Surface Runoff

Surface runoff, or overland flow, is the portion of the rain which is not absorbed by the soil and does not accumulate on the surface, but runs down-slope and collects in gullies and streams. Runoff can occur only when rain intensity exceeds the infiltration rate. Even then, however, runoff does not begin immediately, as the excess rain first collects in surface depressions and forms puddles, whose total volume is termed the *surface storage capacity*. Only when the surface storage is filled and the puddles begin to overflow does runoff begin. The rate of the runoff flow depends upon the excess of rain intensity over the infiltration rate. Obviously, the surface storage also depends on the slope, as well as on the roughness of the soil surface.

In agricultural fields, runoff is generally undesirable, since it results in loss of water and often causes erosion, the amount of which increases with increasing rate and velocity of runoff. The way to prevent erosion is to protect the soil surface against raindrop splash (e.g., by mulching), to increase soil infiltrability and surface storage, and to obstruct overland flow so as to prevent it from gathering velocity. Maintenance and stabilization of soil aggregation will minimize slaking and detachment of soil particles by raindrops and running water. A crusted or compacted soil generally has a low infiltration rate and therefore will produce a high rate of runoff. Proper tillage, especially on the contour, can increase infiltration and surface storage capacity, thus reducing runoff (Burwell and Larson, 1969).

In arid regions, it is sometimes desirable to induce runoff artificially in order to supply water for human, industrial, or agricultural use (Hillel *et al.*, 1967).

K. Summary

An important physical property of a soil is the rate at which it can absorb water supplied to its surface. This rate, termed *soil infiltrability*, depends on the following factors:

(1) Time from the onset of the rain or irrigation: The infiltration rate is apt to be relatively high at first, then to decrease, and eventually to approach a constant rate that is characteristic for the soil.

(2) Initial water content: The wetter the soil is initially, the lower will be the initial infiltrability (owing to smaller suction gradients) and the quicker will be the attainment of the final (constant) rate, which itself is generally independent of the initial water content.

(3) Hydraulic conductivity: The higher the saturated hydraulic conductivity of the soil is, the higher its infiltrability tends to be.

(4) Soil surface conditions: When the soil surface is highly porous and of "open" structure, the initial infiltrability is greater than that of a uniform

soil, but the final infiltrability remains unchanged, as it is limited by the lower conductivity of the transmission zone beneath. On the other hand, when the soil surface is compacted and the profile covered by a surface crust of lower conductivity, the infiltration rate is lower than that of the uncrusted (uniform) soil. The surface crust acts as a hydraulic barrier, or bottleneck, impeding infiltration. This effect, which becomes more pronounced the thicker and the denser the crust, reduces both the initial and the final infiltration rate. A soil of unstable structure tends to form such a crust during infiltration, especially as the result of the slaking action of beating raindrops. In such a soil, a plant cover or a surface mulch of plant residues can serve to intercept and break the impact of the raindrops and thus help to prevent crusting.

(5) The presence of impeding layers inside the profile: Layers which differ in texture or structure from the overlying soil may retard water movement during infiltration. Perhaps surprisingly, clay layers and sand layers can have a similar effect, although for opposite reasons. The clay layer impedes flow owing to its lower *saturated* conductivity, while a sand layer retards the wetting front (where unsaturated conditions prevail) owing to the lower *unsaturated* conductivity of the sand. Flow into a dry sand layer can take place only after the pressure head has built up sufficiently for water to move into and fill the large pores of the sand.

GENERIC QUALITY ASSURANCE PROJECT PLAN (QAPP)

FOR THE

INDUSTRIAL STORMWATER INSPECTIONS

November 2011

Prepared by EPA Region 10 Quality Staff

QAPP APPROVAL:

______________________________ Date: 11/15/2011

Ed Kowalski, Director, USEPA Region 10
Office of Compliance and Enforcement

______________________________ Date: 11/15/2011

for **Kimberly A. Ogle, Unit Manager, USEPA Region 10**
NPDES Compliance Unit, Office of Compliance and Enforcement

______________________________ Date: 11/15/11

Ginna Grepo-Grove, QA Manager, USEPA Region 10
Office of Environmental Assessment

TABLE OF CONTENTS

1.0 Project Management

1.1 Distribution List

Copies of the completed/signed project plan should be distributed to:

Name	Title	Mail Stop	Phone Number	e-Mail Address
Joe Roberto	NPDES Compliance Unit	OCE-133	(206) 553-1669	Roberto.Joseph@epa.gov
Kristine Karlson	NPDES Compliance Unit	OCE-133	(206) 553-0290	Karlson.Kristine@epa.gov
Jennifer Crawford	RSCC	OEA-095	(206) 553-6261	Crawford.Jennifer@epa.gov
Don Matheny	QA Officer	OEA-095	(206) 553-2599	Matheny.Don@epa.gov
Gerald Dodo	Supervisor (Chemistry)	LAB	(360) 871-8728	Dodo.Gerald@epa.gov
TBD	Lab Manager	Contract Lab	TBD	TBD

Summary of analytical results shall be sent to the EPA Inspector. Electronic copies of data are not required unless specifically requested. Contract labs may be given a copy of the Industrial Stormwater Site Specific Inspection Plan (ISSSIP) Analytical Table (Data Quality Objective Summary) for use in providing analytical support.

1.2 Project/ Task Organization

This section identifies the personnel involved in Industrial Stormwater Facility inspection sampling and analytical activities and defines their respective roles and responsibilities in the process.

1. Inspector

The inspector conducts the inspection under the authority provided by the Clean Water Act. The inspector's responsibility is to prepare a final inspection report based on the results of the inspection conducted and the sample analytical data obtained from the laboratory. In conjunction with the inspection, the inspector shall also be responsible for:

- Site inspection and the recording of observations (i.e., field log);
- Documenting the location of site using GPS;
- Conducting dye tracer tests as appropriate;
- Conducting direct readings such as pH, turbidity, etc..., as appropriate;
- Collecting runoff water, effluent samples, soils or sediments as appropriate;
- Coordinating with the Regional Sample Control Center (RSCC) for a regional project code and sample identification numbers
- Coordinating with the mobile EPA or commercial laboratory for sample analyses, as appropriate;
- Maintaining sample documentation, including chain of custody, photographs, and receiving sample analytical results.

All of these tasks shall be performed in accordance with the approved QA Project Plan (QAPP) for Industrial Stormwater Facility wet weather inspections. Changes in procedure should be documented in an appropriate addendum to the plan or sample alteration form (Attachments 1 and 2) and included with the ISSSIP in Appendix A.

2. *Regional Sample Control Center (RSCC)*

The EPA Region 10 RSCC is located within the Office of Environmental Assessment (OEA). Based on information provided in the ISSSIP, the role of the RSCC is to:

- coordinate support with the EPA Region 10 Manchester Environmental Laboratory (MEL)
- schedule sample deliveries and timeframes with MEL,
- provide Regional sample ID numbers, Project Codes and Account Numbers
- sign / concurrence on ISSSIP

3. *Quality Assurance Officer (QAO)*

The QAO is part of the Quality Staff and is located in the Environmental Services Unit in OEA. The QAO is authorized by the Regional QA Manager (RQAM) to act as his/her designee. The QAO reviews / approves the final Generic QAPP, acts as the alternate RSCC and signs/concurs on ISSSIP.

4. *Analytical Laboratory- Manchester Environmental Laboratory (MEL) or Contract Lab*

MEL is the USEPA Region 10 Environmental Laboratory. The Lab's physical address is:

7411 Beach Drive E,
Port Orchard, WA 98366

For these inspections, MEL (or a contract lab) is responsible for the following tasks:

- providing "certified clean" sample containers and preservatives,
- performing analysis of samples,
- data generation, reduction, review and verification
- submission of analytical results, data print-outs (if requested) and QC summary results

In the event that turbidity analysis cannot be performed in the field, a sample may be collected for analysis by MEL. In some cases, samples may need to be shipped to sub-contracted commercial or State labs due to sample holding time issues or laboratory availability.

1.3 Problem Definition/ Background

1.3.1 Background

The Federal and State National Pollutant Discharge Elimination System (NPDES) program monitor and regulate the discharge of pollutants from point sources to waters of the United States. Facilities regulated under the Industrial Stormwater General Permit are point sources, as defined by the CWA [Section 502(14)]. For the purposes of this plan, these regulated facilities will be referred to as: "Industrial Stormwater Facilities". A wet weather initiative for fiscal year 2012 will be implemented for EPA inspectors to conduct NPDES inspections at Industrial Stormwater Facilities. The main goal of this initiative is to conduct the inspections during rain events in order to locate and collect observable discharges running off the site.

The purpose of this Quality Assurance Project Plan (QAPP) is to provide EPA Credentialed Inspectors from the Office of Compliance and Enforcement (OCE), Region 10 State Operations Offices and the Office of Environmental Assessment (OEA) with a basic Plan that will address the Data Quality

Objectives (DQO) required for these Industrial Stormwater Facility site-specific project inspections and provide guidelines on sample collection, sample documentation, analytical methods, and data validation and interpretation of data deliverables. This document was prepared in compliance with the EPA Policy CIO 2106.0, October 20, 2008 and the Agency QA document QA-G5, "*Guidance for Quality Assurance Project Plans", Final Version: December, 2002*.

1.3.2 Objectives/Scope

Determine compliance of observable discharges from Industrial Stormwater Facilities during wet weather events with the Clean Water Act through the collection of samples of opportunity from the facilities inspected. For the purposes of defining the sampling and analytical of this wet weather initiative, facility types have been placed in the following 4 categories in accordance with the Industrial Stormwater General Permit. These are:

- **Food & Chemical** (*Chemical & Allied Products, Food & Kindred Products*)
- **Metals & Auto** (*Primary Metals, Metals Mining, Auto Salvage & Scrap Recycling, Metals Fabrication*)
- **Hazardous Waste** (*Hazardous Waste Treatment, Storage & Disposal Facilities and Dangerous Waste Recyclers subject to provisions of Resource Conservation & Recovery Act Subtitle C*)
- **Timber** (*Timber Product Industry, Paper & Allied Products*)

1.4 Project/ Task Description and Schedule

1.4.1 Project/Task Description

This Generic QAPP is developed for the purpose of supporting (announced or unannounced) Industrial Stormwater inspections that may be performed as part of the NPDES program. Analysis for pH and turbidity in addition to observations for flow, oil sheens and dye tests will be conducted on-site by the inspector. Samples for metals and PCB determinations will be analyzed by MEL or a sub-contracted commercial lab. The sub-contracted lab must be accredited and /or certified by a recognized accrediting authority such as NELAP or the Washington State Department of Ecology accrediting program. Samples for other parameters, if needed, will be analyzed by MEL or a sub-contracted commercial lab. All of the analyses will be performed in accordance with the analytical methodologies and QC requirements specified in Table 3 - Data Quality Objectives Summary of this Generic QAPP. See the sample collection section and specific analyses that will be performed.

1.4.2 Schedule of Tasks

Table 1 – Activity Schedule and Tentative Start and Completion Dates

Activity	Estimated Start Date	Estimated Completion Date
Submit ISSSIP to RSCC / Receive Sample IDs, etc.	2-4 weeks prior to field mobilization	
Mobilize to Sites	See IS-SSIP	
Sample Collection		
On-site Analysis of Samples		
Data Review/Verification/Reporting data to Inspector		8 Weeks after receipt of samples
Target Completion Date		TBD by Inspector / Program

1.4.3 Industrial Stormwater Site-Specific Inspection Plan (ISSSIP)

This Industrial Stormwater generic QAPP shall cover the QA requirements of all Wet Weather initiative Industrial Stormwater inspections performed by EPA inspectors within Region 10. After program and RQAM approval of this generic QAPP, the inspectors are only required to fill-out the summary of this generic QAPP called the "Industrial Stormwater Site-Specific Inspection Plan (ISSSIP)". The ISSSIP is a two-page summary of the sampling, analysis and QA requirements that may be performed during facility inspections. The ISSSIP lists the following required information:

- **Name of facilities inspected,**
- **Name of the inspector and contact information,**
- **Approximate number of samples that will be collected (Table 3),**
- **Chemical parameters identified for laboratory analysis (Table 3)**

The Data Quality Objectives Summary in Table 3 is also a part of the ISSSIP. The inspector(s) check mark the parameters listed in Table 3 applicable to the samples of opportunity collected from the types of facilities inspected. A completed ISSSIP is submitted to the RSCC 2-4 weeks prior to sample collection in order to allow for adequate time to reserve laboratory space and the assignment of a project code, sample IDs and filing. The first page of ISSSIP contains the project, the account code, EPA sample numbers assigned for inspection, list of facilities inspected, address, contact person and phone number, the names of inspectors conducting the inspection and their respective environmental organization affiliations, the total number of samples collected per facility, and the parameters that were determined. The second page of ISSSIP is the Table 3 – the Summary of Data Quality Objectives listing the number of samples collected, parameters for analysis, analytical procedures and methodologies and the precision, accuracy and other DQO requirements for analysis. If applicable, Attachment 1 and 2 (Sample Alteration and Corrective Action Forms), may also be included with the ISSSIP. The ISSSIP is submitted to the QA Office for review and approval before a scheduled sampling event or immediately after collecting samples of opportunity. A blank 2 page ISSSIP to be filled out and submitted by the inspectors is attached In Appendix A of this Generic QAPP.

1.5 Data Quality Objectives and Criteria for Measurement Data

Data Quality Objectives (DQOs) are the quantitative and qualitative terms inspectors and project managers use to describe how good the data needs to be in order to meet the project's objectives. DQOs for measurement data (referred to here as data quality indicators) are precision, accuracy, representativeness, completeness, comparability, sensitivity and measurement range. The overall QA objective for analytical data is to ensure that data of known and acceptable quality are provided. To achieve this goal, data must be reviewed for 1) representativeness, 2) comparability, 3) precision, 4) accuracy (and bias), 5) completeness and 6) sensitivity. Precision, accuracy, sensitivity, completeness, sample representativeness and data comparability are necessary attributes to ensure that analytical data are reliable, scientifically sound, and legally defensible. Each analytical result or set of results generated should be fully defensible in any legal action, whether administrative, civil, or criminal.

<u>Precision:</u> The precision of each test depends on the number of tubes used for the analysis. Samples in duplicate will be analyzed on a 10 % frequency (1 per 10 samples collected). The precision is evaluated using the Relative Percent Difference (RPD) values between the duplicate sample results.

<u>Accuracy:</u> Accuracy and bias will be evaluated by the use percent recovery (%R) of the target analyte in spiked samples and also the recoveries of the surrogates in all samples and QC samples.

$$\% \text{ Recovery} = \frac{SQ - NQ}{S} \times 100$$

SQ = quantity of spike or surrogate found in sample
NQ = quantity found in native (un-spiked) sample
S = quantity of spike or surrogate added to native sample

Representativeness is the degree to which data from the project accurately represent a particular characteristic of the environmental matrix which is being tested. Representativeness of samples is ensured by adherence to standard field sampling protocols and to standard laboratory methods and protocols. The design of the sampling scheme and number of samples should provide a representativeness of each matrix or product of the chemical processes being sampled.

Comparability is the measurement of the confidence in comparing the results of one sampling event with the results of another achieved by using the same matrix, sample location, sampling techniques and analytical methodologies.

Completeness: Completeness is the percentage of valid results obtained compared to the total number of samples taken for a parameter. Since sampling from inspections are usually grab and limited in number of samples, the number of valid results obtained from the analyses are expected to be equal or better than 95%. Percent completeness may be calculated using the following formula:

$$\% \text{ Completeness} = \frac{\# \text{ of valid results}}{\# \text{ of samples taken}} \times 100$$

Sensitivity is the capability of a method or instrument to discriminate between measurement responses representing different levels of the variable of interest. Field and laboratory measurements need to have the required sensitivity to allow for an evaluation of the data against the applicable regulatory criteria.

The QA objectives outlined, above, will be evaluated in conjunction with the data validation process.

1.6 Special Training Requirements/Certification

Inspectors are required to complete the 24-hour Basic Health and Safety training. The inspectors will obtain a basic health and safety training certification from the 24-hour training which should be maintained current by attending an 8-hour safety training refresher course every year. The inspectors must also have a signed and current "credential" certifying the bearer as "Authorized to Conduct Investigations and Inspections Pursuant to All Federal Laws Administered by the United States Environmental Protection Agency". All of the training courses listed above are provided by EPA Region 10. Furthermore, sampling and sample documentation skills are also assured by the "mentoring" provided by the senior inspectors in the field.

The laboratories performing the sample analysis for this program are NELAP and/or State accredited. Chemists performing the analytical work for this project have extensive knowledge, skill and demonstrated experience in the execution of the analytical methods being requested.

1.7 Documentation and Records

Complete documentation for inspections may include but is not limited to the following forms, which have to be completed and collated by the EPA Inspector:

- Investigation Report
- Records Inspection Checklist
- Chain of Custody Logs
- Record of Sampling
- Laboratory Analysis Reports
- Photographs, Sketches, Paper Copies, Chemical Labels, MSDS, Application Records or other documentation.

Investigators will maintain field notes in a bound notebook and all documents, records, and data collected will be kept in a case file and submitted to the program office with the final inspection report.

The following documents will be archived at the Manchester Environmental Laboratory or the designated laboratory performing the analysis: (1) signed hard copies of sampling and chain-of-custody records (2) electronic and hard copy of analytical data including extraction and sample preparation bench sheets, raw data and reduced analytical data.

The laboratory will store the above records, data, and other analytical documentation as per their established SOP.

2.0 Measurement/ Data Acquisition

2.1 Sampling Process Design (Experimental Design)

Prior to compliance inspections, the EPA Inspector will review and evaluate facility files, if available, which may include facility background information, historical ownership, facility maps depicting general geographic location, property lines, surrounding land uses, a summary of all possible source areas of contamination, a summary of past permits requested and/or received, any enforcement actions and their subsequent responses and a list of documents and studies prepared for the facility, records and inspection reports from previous compliance site visits.

Based on the data and visual inspection of the facility, samples of opportunity on an “as needed” basis will be collected for analysis to characterize the pollutants and determine if they are in compliance with the Clean Water Act.

2.2 Inspection and Sample Collection Procedures

2.2.1 Health and Safety

Inspectors visiting Industrial Stormwater facilities need to be aware of the physical hazards of these facilities. Sharp objects imbedded in walking areas, heavy auto parts, precarious stacks of material and heavy moving equipment all present physical hazards which inspectors need to consider upon entry. Boots with steel toes and shanks are highly recommended. Other considerations such as the use of nitrile gloves, hard hats, ear protection, orange vests and safety glasses are also recommended.

2.2.2 Location

Inspectors should use the Global Positioning System receiver (GPS) for documenting locations of facilities inspected. A calibrated GPS instrument can be checked out through Mr. Matt Gubitosa of the Environmental Characterization Unit, OEA, phone number: (206) 553-4059.

2.2.3 Sample Collection

Sample collection methods can vary between standard operating procedures used by samplers and different conditions encountered in the field. The following is provided as general guidance for samplers. Samplers should document in their field records the actual method used during sample collection.

If samples are collected manually, nitrile gloves should be worn to protect the sampler. Also, the use of safety glasses should be considered. Additional safety information should be covered in a site safety plan or pre-inspection safety briefing.

When a discharge point is identified, the sampler should consider collecting, when possible, samples at a minimum of one collection point. This collection point should be obtained at the discharge point. More sample collection points may be collected by the inspectors if necessary.

To the extent possible, take the sample by holding the bottle near its base in the hand and plunging it, neck downward, below the surface. Use an extension pole if needed to keep from walking into the effluent stream and stirring up the sampling area. Turn bottle until neck points slightly upward and mouth is directed towards the current. If there is no current, create a current by pushing bottle forward horizontally in a direction away from the hand. After collection, carefully recap the sample bottle securely. Sample bottles do not need to be filled to the rim. DO NOT RINSE any sample bottles for collection of waters.

Soil and/or sediment samples should be collected using a dedicated stainless steel spoon and mixing bowl. These samples are carefully placed in wide mouth glass container and capped.

The sample containers should be labeled with:

- Regional Sample Identification Number
- Date & Time of Sample Collection
- Sampler's name
- Project Code
- Preservative used
- Type of analysis

This information should be written on the label using an indelible, waterproof ink. Sample containers should be placed individually in sealed plastic bags and stored on ice immediately following collection until lab receipt and custody relinquishment is complete. Proper chain of custody procedures must be followed at all times.

If analysis of additional parameters is needed in a specific case, additional sample containers may be needed. Required sample volume, container type, preservation techniques, and holding times for parameters likely to be sampled are included in (Table 3). <u>Inspectors should use their discretion and the</u>

Facility Types (Table 3) to determine which parameters should be used to document violations at a particular facility and are encouraged to discuss this with the NPDES Compliance Program representatives and laboratory/RSCC in order to ensure proper collection and preservation.

2.2.4 Sample Collection Equipment

Equipment needs will vary from inspection to inspection. The list in Table 2 (below) provides suggestions to be considered prior to leaving for the field.

Table 2 – Suggested Sample Equipment for Industrial Stormwater Field Inspections

General	Safety	Emergency
Inspector Credentials Field Notebook Camera Global Positioning System Receiver (GPS) Waterproof Pens & Markers Clipboard flashlight Extension Sampling Pole Sample containers Bubble wrap Ice Chest Extra Set of Coveralls	Water Proof Boots (steel toe/shank) Rain gear Rubber, Latex or Nitrile gloves Soap, towels, and water for washing hands Ear protection Eye protection Hard hat	First Aid Kit Phone numbers Cell Phone

2.2.5 Shipping Requirements

All of the samples are hand-delivered to the laboratory analyzing the samples. Samples for laboratory analysis will be hand-delivered to the MEL within the prescribed holding times. Sufficient ice must be provided to ensure that samples remain cold until received and processed by the laboratory.

2.2.6 Decontamination Procedures

Samples will be collected using dedicated clean sampling devices and sample collection gear. Sampling devices and sample collection gear such as rain gear, rubber boots and gloves will be cleaned and decontaminated as appropriate using a phosphate-free detergent. Inspectors will follow the proper health and safety procedures when collecting and handling samples to minimize or avoid contamination.

2.3 Analytical Methods Requirements

Measurement parameters for the Industrial Stormwater facility inspections may be conducted in the field and/or by the laboratory. Analytical methods have been selected that meet the applicable NPDES regulatory requirements (40 CFR 136). Table 3 -Data Quality Objective Summary lists the parameters that can be measured under this plan, the accuracy, precision, sensitivity, preservation, and holding time requirements.

2.4 Quality Control Requirements

Quality Control procedures for analyte measurements will be according to the requirements specified in the method that will be used in the analysis.

2.5 Instrument/Equipment Testing, Inspection and Maintenance Requirements

Field and laboratory personnel will follow their standard operating procedures for any preventative maintenance required on laboratory instruments or systems used for this project. For field instrumentation, a citation of the SOP should be noted in the field logs.

2.6 Instrument Calibration and Frequency

Field maintenance and calibration will be performed where appropriate prior to use of the instruments and in accordance with the applicable Region 10 Standard Operating Procedure. The laboratory will follow the calibration procedures found in the methods listed in Table 3 or in the laboratory's SOPs. For field pH, a second source standard will be used to verify instrument calibration prior to use and at the end of the day.

2.7 Inspection/Acceptance Requirements for Supplies and Consumables

Sample bottles will be appropriately cleaned as per MEL SOP MIG001A or certified clean from the supplier. Inspectors will make note of the information on the certificate of analysis that accompanies sample jars to ensure that they meet the specifications and guidance for contaminant free sample containers.

2.8 Data Acquisition Requirements (non-Direct Measurements)

All monitoring data collected under this Generic QAPP will be primary data (collected by EPA). No secondary (existing) monitoring data must be acquired for these inspections.

2.9 Data Management

A field log notebook, photos, GPS location data and the Field Sample and Chain of Custody Data Sheets will be used to document the sampling and inspection activities. For each sample location, the following will be recorded in the notebook:

- Facility Name & Address
- Regional Sample Identification Number
- Date & Time of Sample Collection
- Physical Description of each Sample Collection Point
- Weather Conditions
- Color of Sample (water)
- Sample Matrix (water, soil, sediment)
- Sample Appearance
- Applicable Field Measurements

The Field Sample and Chain of Custody Data Sheets will have the following information:

- Facility Name
- Project Code
- Regional Sample Identification Number
- Date & Time of Sample Collection
- Sampler's name & initials

- Sample Location

If applicable, a suffix l -FD will be appended to the sample identified as the field duplicate. For fixed laboratory analyses, field duplicates will be assigned a separate unique sample identifier and will be submitted ‘blind’ to the analytical laboratory. Analytical duplicate results will be reported with a trailing -DU (analytical duplicate) or D.

All inspection reports including those for potential enforcement cases will be completed within a timeframe agreed to between the Inspector and Program. Validated laboratory results and interpretation (if necessary) will be appended. Reports will be maintained as enforcement confidential documents until release is approved by the USEPA Office of Regional Counsel (ORC). Photographs and other supporting data along with the inspection report will be used to determine NPDES compliance.

All laboratory analytical data generated in support of these inspections will be processed, stored, and distributed according to laboratory’s SOPs.

3.0 Assessment/Oversight

3.1 Assessments and Response Actions

The inspector will be responsible for reviewing field log notebooks for accuracy and completeness within 48 hours of each inspection. Sample results provided to the inspector by the laboratory will be appended to the inspection reports. The inspector will compare the sample information in the field log notebooks with the analytical results appended to the inspection report to ensure that no transcriptions errors have occurred.

RPDs between field duplicate and analytical duplicate measurements will be calculated by the laboratory. RPD’s greater than the project requirements will be noted in the inspection report.

Laboratories routinely perform performance checks using different program specific quarterly blind and check standards. Each method of analysis requires specific QA/QC runs that must be complied with by the laboratory performing the analysis. An internal review and verification of the data and results are also routinely conducted by the appropriate supervisors and the Laboratory QA Coordinator. No additional audits will be performed on the laboratory for this project.

Corrective action procedures that might be implemented from QA results or detection of unacceptable data will be developed if required and documented in Attachment 2.

3.2 Reports to Management

Only the data review & verification reports with the properly qualified data shall be provided by the laboratory to the inspectors. If, for any reason, the schedules or procedures above cannot be followed, the EPA Inspector must complete the Attachment 1- Sample Alteration Form (SAF). The SAF should be reviewed and approved by the QAO. The laboratory should be given a copy of the QAO approved SAF for reference and project file.

4.0 Data Validation and Usability

4.1 Data Review, Validation, and Verification Requirements

The criteria for the validation will follow those specified in this QA plan and the criteria specified in the methods.

4.2 Validation and Verification Methods

All data generated shall be reviewed and verified in accordance with the QA/QC requirements specified in the methods, and the technical specifications outlined in the QAPP. The summary of all analytical results will be reported to the EPA Inspector. The raw data for this project shall be maintained by the laboratory. Data review will be performed by the laboratory for all the analyses prior to the release of data (which will occur approximately 8 weeks after receipt of samples). The laboratory will also archive the analytical data into their laboratory data management system.

4.3 Reconciliation with User Requirements

All data and related information obtained during the course of this project will be included in a data report package.

Table 3 – Industrial Stormwater Generic QAPP Analytical Data Quality Objectives Summary

Analytical Group	Number of Samples[1]	# of Field QA Samples: Dups / Blanks (10% dup or 1 per day)	MS / MSD Samples (5% or 1/20 samples)	Matrix	Method	Method Reporting Limits (Sensitivity)	Accuracy	Precision (RPD)	Complete-ness	Preservation	Volume, Container	Holding Time (days)
ALL INDUSTRIAL STORMWATER GENERAL PERMIT FACILITIES – Laboratory Measurements												
Total & Dissolved Metals[2]- No Hg		Y	Y	water	200.8	see footnote[2]	75-125%	± 20RPD	95%	HNO_3 to pH<2, Cool on Ice ≤ 6°C	1 Liter (P)[3]	180 days
Total Hardness as CaCO3 (Calc.)		Y	Y	water	SM 2340B	0.30 mg/L	75-125%	± 20RPD	95%	HNO_3 to pH<2, Cool on Ice ≤ 6°C	1 Liter (P)[3]	180 days
FOOD & CHEMICAL FACILITIES – Laboratory Measurements												
Biological Oxygen Demand		Y	NA	water	SM 5210B	4 mg/L	75-125%	± 20RPD	95%	Cool on Ice ≤ 6°C	1 Liter (P, G) - FULL	48 Hours
Nitrate/Nitrite as Nitrogen		Y	Y	water	353.2	0.1 mg/L	75-125%	± 20RPD	95%	H_2SO_4 to pH<2, Cool on Ice ≤ 6°C	1 Liter (P) - combine in 1 bottle	28 days
Total Phosphorus		Y	Y	water	365.1	0.1 mg/L	75-125%	± 20RPD	95%	H_2SO_4 to pH<2, Cool on Ice ≤ 6°C		28 days
METALS & AUTO FACILITIES – Laboratory Measurements												
Total & Dissolved Hg[2]		Y	Y	water	245.1	0.2 µg/L	75-125%	± 20RPD	95%	HNO_3 to pH<2, Cool on Ice ≤ 6°C	NONE: Included in TM/DM 1L(P)	28 days
Metals[2] (including Hg)		Y	Y	sediment	200.7 / 7471B	0.2-10 mg/kg	75-125%	± 20RPD	95%	Cool on Ice ≤ 6°C	4 oz. wide mouth (G)	180 days / Hg 28 days
TPH-Diesel Range (plus motor oil)		Y	Y	water	NWTPH-Dx	0.25 mg/L	50-150%	± 35RPD	95%	Cool on Ice ≤ 6°C	2x500mL amber (G) Teflon lined cap, 5x500mL for samples with QC	7 days
PCBs		Y	Y	water	8082	30 µg/ L	50-150%	± 35RPD	95%	Cool on Ice ≤ 6°C	2x40mL clear vials Teflon lined cap, 5x40mL for samples with QC	14 days to extract / 40 days to analysis
				sediment		0.1 mg/kg					8 oz. wide mouth (G))	
HAZARDOUS WASTE FACILITIES – Laboratory Measurements												
TSS		Y	NA	water	I-3765-85	2 mg/L	NA	± 20RPD	95%	Cool on Ice ≤ 6°C	1 Liter (P) - FULL	7 days
Total & Dissolved Hg[2]		Y	Y	water	245.1	0.2 µg/L	75-125%	± 20RPD	95%	HNO_3 to pH<2, Cool on Ice ≤ 6°C	NONE: Included in TM/DM 1L(P)	28 days
Metals[2] (including Hg)		Y	Y	sediment	200.7 / 7471B	0.2-10 mg/kg	75-125%	± 20RPD	95%	Cool on Ice ≤ 6°C	4 oz. wide mouth (G)	180 days / Hg 28 days
TPH-Diesel Range (plus motor oil)		Y	Y	water	NWTPH-Dx	0.25 mg/L	50-150%	± 35RPD	95%	Cool on Ice ≤ 6°C	2x500mL amber (G) Teflon lined cap, 5x500mL for samples with QC	7 days
TIMBER FACILITIES – Laboratory Measurements												
TSS		Y	NA	water	I-3765-85	2 mg/L	NA	± 20RPD	95%	Cool on Ice ≤ 6°C	1Liter (P) - FULL	7 days
ALL INDUSTRIAL STORMWATER GENERAL PERMIT FACILITIES – Field Measurements												
Turbidity		Y	NA	water	180.1	0.1 NTU	NA	± 20RPD	100%	Cool on Ice ≤ 6°C	100 ml P, G	48 hours
pH		Y	NA	water	4500-H+ B	0.1 pH units	NA	± 0.5 pH Units	100%	Not Required	100 ml P, G	Analyze Immediately
Oil Sheen		NA	NA	water	NA	Visible	NA	NA	NA	NA	NA	Onsite observation

*All samples must be collected as grabs. Sample containers for water cannot be rinsed with sample water (fill once to the top of the neck, then cap immediately).

[1] - Sample number includes QA samples and Matrix Spike / Matrix Spike Duplicate (MS/MSD) samples listed in the next two columns. P,G - Plastic, Glass.

[2] – Priority Pollutant metals (water reporting limits in µg/ L): antimony (1.0), arsenic (1.0), beryllium (0.1), cadmium (0.2), chromium (2.0), copper (2.0), lead (0.5), mercury (0.2), nickel (0.5), selenium (2.0), silver (1.0), thallium (1.0), zinc (3.0). Samples for Dissolved Metals analysis must be filtered (0.45 micron) within 15 minutes of collection.

[3] – Samples for Total Hardness and Total Metals /Mercury analysis may be combined into one 1L (P). This does not include Dissolved Metals samples.

Industrial Stormwater Inspection Generic QAPP

Appendix A: Site Specific Inspection Plan (IS-SSIP)

This IS-SSIP will be prepared and used in conjunction with the Generic Industrial Stormwater Inspection QAPP for collecting samples of opportunity during announced and unannounced inspections. Please refer to the Generic QAPP for specific details regarding IS-SSIP.

Project Account Code*	**Sample Numbers***	**EPA Inspectors/Phone Numbers/Mail Stop**

*As assigned by RSCC, one per facility inspected. Sample numbers are assigned according to the week number of collection.

COOPERATING AGENCIES/PARTIES INVOLVED:

Contact Person	Agency	Phone Number

FACILITY INFORMATION

Facility Name	Address	Contact person	E-mail/phone Number

TENTATIVE PROJECT SCHEDULE

Activity	Est. Start Date	Est. Completion Date	Comments
Mobilize to Site			
Sample Collection			
Laboratory Receipt of Samples			
Target Completion Date			Final data delivery normal TAT is 8wks from sample receipt.

DATA DISTRIBUTION

Name and Mail Stop	Electronic	Hard Copy

Concurrence with the IS-SSIP:

RSCC/QA Reviewer: ____ Date: ____________

Printed Name and Signature

Inspector: ____ Date: ____________

Printed Name and Signature

Instructions

Submit both pages of the IS-SSIP to the RSCC for laboratory coordination/sample numbers/project information and to the QAO for review and concurrence. Complete, sign, and Email the IS-SSIP to the EPA R10 RSCC, Crawford.Jennifer@epa.gov (206-553-6261) or to the back-up RSCC Matheny.Don@epa.gov when needed (206-553-2599).

Note RE Page 2 of the IS-SSIP - Table of DQOs: Do not remove analytes from this table. Fill in the number of samples (column 2) for each applicable analysis/matrix. If the number of samples (column 2) is left blank for a particular analysis, the RSCC/QAO and lab will presume that the analysis is not required for the inspection.

Industrial Stormwater Inspection Generic QAPP: Site Specific Inspection Plan (IS-SSIP)

IS-SSIP Analytical Data Quality Objectives Summary Table*

Analytical Group	Number of Samples[1]	# of Field QA Samples: Dups / Blanks (10% dup or 1 per day)	MS / MSD Samples (5% or 1/20 samples)	Matrix	Method	Method Reporting Limits (Sensitivity)	Accuracy	Precision (RPD)	Complete-ness	Preservation	Volume, Container	Holding Time (days)
ALL INDUSTRIAL STORMWATER GENERAL PERMIT FACILITIES – Laboratory Measurements												
Total & Dissolved Metals[2]- No Hg		Y	Y	water	200.8	see footnote[2]	75-125%	± 20RPD	95%	HNO_3 to pH<2, Cool on Ice ≤ 6°C	1 Liter (P)[3]	180 days
Total Hardness as CaCO3 (Calc.)		Y	Y	water	SM 2340B	0.30 mg/L	75-125%	± 20RPD	95%	HNO_3 to pH<2, Cool on Ice ≤ 6°C	1 Liter (P)[3]	180 days
FOOD & CHEMICAL FACILITIES – Laboratory Measurements												
Biological Oxygen Demand		Y	NA	water	SM 5210B	4 mg/L	75-125%	± 20RPD	95%	Cool on Ice ≤ 6°C	1 Liter (P, G) - FULL	48 Hours
Nitrate/Nitrite as Nitrogen		Y	Y	water	353.2	0.1 mg/L	75-125%	± 20RPD	95%	H_2SO_4 to pH<2, Cool on Ice ≤ 6°C	1 Liter (P) - combine in 1 bottle	28 days
Total Phosphorus		Y	Y	water	365.1	0.1 mg/L	75-125%	± 20RPD	95%	H_2SO_4 to pH<2, Cool on Ice ≤ 6°C		28 days
METALS & AUTO FACILITIES – Laboratory Measurements												
Total & Dissolved Hg[2]		Y	Y	water	245.1	0.2 µg/L	75-125%	± 20RPD	95%	HNO_3 to pH<2, Cool on Ice ≤ 6°C	NONE: Included in TM/DM 1L(P)	28 days
Metals[2] (including Hg)		Y	Y	sediment	200.7 / 7471B	0.2-10 mg/kg	75-125%	± 20RPD	95%	Cool on Ice ≤ 6°C	4 oz. wide mouth (G)	180 days / Hg 28 days
TPH-Diesel Range (plus motor oil)		Y	Y	water	NWTPH-Dx	0.25 mg/L	50-150%	± 35RPD	95%	Cool on Ice ≤ 6°C	2x500mL amber (G) Teflon lined cap, 5x500mL for samples with QC	7 days
PCBs		Y	Y	water	8082	30 µg/ L	50-150%	± 35RPD	95%	Cool on Ice ≤ 6°C	2x40mL clear vials Teflon lined cap, 5x40mL for samples with QC	14 days to extract / 40 days to analysis
				sediment		0.1 mg/kg					8 oz. wide mouth (G))	
HAZARDOUS WASTE FACILITIES – Laboratory Measurements												
TSS		Y	NA	water	I-3765-85	2 mg/L	NA	± 20RPD	95%	Cool on Ice ≤ 6°C	1 Liter (P) - FULL	7 days
Total & Dissolved Hg[2]		Y	Y	water	245.1	0.2 µg/L	75-125%	± 20RPD	95%	HNO_3 to pH<2, Cool on Ice ≤ 6°C	NONE: Included in TM/DM 1L(P)	28 days
Metals[2] (including Hg)		Y	Y	sediment	200.7 / 7471B	0.2-10 mg/kg	75-125%	± 20RPD	95%	Cool on Ice ≤ 6°C	4 oz. wide mouth (G)	180 days / Hg 28 days
TPH-Diesel Range (plus motor oil)		Y	Y	water	NWTPH-Dx	0.25 mg/L	50-150%	± 35RPD	95%	Cool on Ice ≤ 6°C	2x500mL amber (G) Teflon lined cap, 5x500mL for samples with QC	7 days
TIMBER FACILITIES – Laboratory Measurements												
TSS		Y	NA	water	I-3765-85	2 mg/L	NA	± 20RPD	95%	Cool on Ice ≤ 6°C	1Liter (P) - FULL	7 days
ALL INDUSTRIAL STORMWATER GENERAL PERMIT FACILITIES – Field Measurements												
Turbidity		Y	NA	water	180.1	0.1 NTU	NA	± 20RPD	100%	Cool on Ice ≤ 6°C	100 ml P, G	48 hours
pH		Y	NA	water	4500-H+ B	0.1 pH units	NA	± 0.5 pH Units	100%	Not Required	100 ml P, G	Analyze Immediately
Oil Sheen		NA	NA	water	NA	Visible	NA	NA	NA	NA	NA	Onsite observation

*All samples must be collected as grabs. Sample containers for water cannot be rinsed with sample water (fill once to the top of the neck, then cap immediately).

1 - Sample number includes QA samples and Matrix Spike / Matrix Spike Duplicate (MS/MSD) samples listed in the next two columns. P,G - Plastic, Glass.

2 - Priority Pollutant metals (water reporting limits in µg/ L): antimony (1.0), arsenic (1.0), beryllium (0.1), cadmium (0.2), chromium (2.0), copper (2.0), lead (0.5), mercury (0.2), nickel (0.5), selenium (2.0), silver (1.0), thallium (1.0), zinc (3.0). For dissolved metals, water samples must be filtered (0.45 micron) within 15 minutes of collection.

Industrial Stormwater Inspection Generic QAPP
Attachment 1 - Sample Alteration Form

Project Name and Number: ____
Sample Matrix: ____
Measurement Parameter: ____

Standard Procedure for Field Collection & Laboratory Analysis (cite reference):

____

____

Reason for Change in Field Procedure or Analysis Variation:

____

____

Variation from Field or Analytical Procedure:

____

____

Special Equipment, Materials or Personnel Required:

____

____

____

____

Initiators Name: ______________________________ Date: _______________________

Inspector: ______________________________________ Date: _______________________

Quality Staff: __________________________________ Date: _______________________

Industrial Stormwater Inspection Generic QAPP
Attachment 2 - Corrective Action Form

Project Name and Number: ____

Sample Dates Involved: ____

Measurement Parameter: ____

Acceptable Data Range: ____

Problem Areas Requiring Corrective Action: _______________________________________
____
____
____

Measures Required to Correct Problem(s): ____
____
____
____

Means of Detecting Problems and Verifying Correction: ______________________________
____
____
____

Initiators Name: ______________________________________ Date: ______________

Inspector: ____ Date: ______________

Quality Staff: ____ Date: ______________

ASSESSMENT OF CURRENT WATER QUANTITY CONDITIONS IN THE GREEN RIVER BASIN

Prepared for:

WRIA 9 Steering Committee

Funded by:

A King Conservation District Grant
For the WRIA 9 Forum of Local Governments

King County Department of Natural Resources and Parks

Washington Department of Ecology

Prepared by:

Northwest Hydraulics Consultants, Inc.

September 2005

ASSESSMENT OF CURRENT WATER QUANTITY CONDITIONS IN THE GREEN RIVER BASIN

Prepared for:

WRIA 9 Steering Committee

Prepared by:

Northwest Hydraulic Consultants, Inc.
16300 Christensen Road, Suite 350
Seattle, Washington 98188
Ph. (206) 241-6000

September 2005

Executive Summary

Current water quantity conditions are assessed in the Green River Basin upstream from River Mile 23.8 (RM 23.8) where Mill Creek (Auburn), the last of the basin's major freely-draining tributaries, enters the Green. In the context of the large Green/Duwamish sub-basins described in other reports, this study focuses on the upper Lower Green, the Middle Green, and the Upper Green River sub-watersheds. Water quantity conditions are evaluated in terms of the monthly mean and 7-day low streamflows at selected locations along the main stem channel and on major tributaries. Current conditions are further defined by the status of land use, water withdrawals, and water exports in the watersheds upstream of each location as of approximately Year 2000.

This report identifies and draws upon the many prior studies which have characterized water resources and uses in the study area. An accompanying CD-ROM disk provides copies of recent digitally-published documents including the December 2000 Habitat Limiting Factors and Reconnaissance Assessment Report for the Green/Duwamish Watershed, the July 2001 Tacoma Water Habitat Conservation Plan for the Green River, and the July 2001 Central Puget Sound Regional Water Supply Outlook. The CD-ROM also includes scanned excerpts of other relevant documents which include water supply plans and hydrogeological reports.

Streamflow statistics representing current conditions were determined for six sites on the main-stem Green River from RM 63.6, just below Howard Hanson Dam, to RM 23.8, just below the confluence with Mill Creek (Auburn). The main-stem channel sites correspond to the locations of active USGS stream gages and major tributary inputs. Streamflow statistics for tributary streams were determined for Mill Creek which joins the Green at RM 23.8, Soos Creek at RM 33.8, and Newaukum Creek at RM 40.7, and for Covington and Jenkins Creeks which are tributaries to Soos Creek. These tributaries drain a combined basin area of 106 square miles and account for 56% of the total study area downstream of the Tacoma Diversion.

Streamflow statistics including the 50% and 90% exceedance values for 7-day low flows and mean monthly flows were chosen to reflect the study context of managing water for both fish and people. Statistics that emphasize low-flow conditions are of interest because low flows can be a limiting factor to fish utilization of streams. It is during low flow that competition for water between fish and for people becomes most critical. Average-flow conditions are also of interest because average flows are relevant to a water budget which evaluates water supplies and demands over monthly and annual time frames in a system with reservoir storage. The flow statistics are presented in Chapter 3.

Chinook, chum, coho, pink, and sockeye salmon and steelhead trout are all found within the study area. Chinook salmon in western Washington, including those in the Green River, was listed as a threatened species under the provisions of the Endangered Species Act on 1 November 1999, and is a focus species for water management actions.

Chinook salmon are present within the Green River from the lower end of the study area to RM 61. Anadromous salmon have been prevented from accessing the upper Green River above RM 61 since 1911 when a diversion dam was constructed by the City of Tacoma for its domestic water supply. Howard Hanson Dam, built in 1963 by the US Army Corps of Engineers, is located 3.5 miles upstream from the diversion. Juvenile Chinook salmon are planted above Howard Hanson Dam by the Muckleshoot Indian Tribe to rear in the Upper Green River sub-watershed. The primary spawning areas for summer/fall Chinook salmon in the study area are the mainstem Green River and major tributaries including Big Soos Creek and Newaukum Creek.

The Howard Hanson Dam is operated for Green River flood control and also to provide low flow augmentation through management of a summer conservation pool of approximately 30,000 acre-feet. Low flow augmentation is managed by the Army Corps of Engineers in consultation with the Muckleshoot Indian Tribe, Washington Department of Fish and Wildlife, Tacoma Public Utilities, and several other public and private organizations. Water management coordination meetings occur about twice a month from spring through fall to balance the habitat needs of salmonids while accommodating a variety of competing uses.

From the perspective of resource managers trying to meet water needs for fish in the mainstem Green River, there is rarely enough water to meet all resource needs. Instream flow needs during the early summer through fall conservation pool allocation period include: (1) protection of wild winter steelhead redds through fry emergence, (2) adequate summer low flows for juvenile steelhead and salmon rearing, and (3) sufficient flows for Chinook spawning. In the majority of years, none of these needs can be fully met. Providing enough water for even one of these needs means compromising the others.

The flow regime on the mainstem Green River is expected to change from current (2001-2004) conditions as a result of new procedures associated with the implementation of the City of Tacoma's second diversion water right. The exercising of that water right and initiation of revised practices are expected to begin in late 2005. The revised practices will include increased withdrawals for municipal supply combined with an additional 20,000 acre feet of water storage for summer withdrawals and new instream flow commitments. Exercising the second diversion withdrawals include a guarantee by Tacoma Public Utilities to provide minimum continuous instream flows in the Green River as measured at the Auburn Gage. The minimum flows will vary with weather conditions during the summer months and will range from 350 cfs in average and wet years to a minimum of 225 cfs in a severe drought year.

While storage-based streamflow augmentation is critical to maintaining adequate summer flows in the Green River, reservoir refill operations also present a challenge. The late winter-spring period from late February through May is important for salmon life stages, and the additional water storage project at Howard Hanson Dam will require more aggressive refill rates which may impact habitat and life-stage survival. Additional efforts and management techniques need to be developed to minimize downstream impacts on fish during refill operations, particularly in years with low snow pack or dry spring conditions when refill-period impacts would be most likely to occur.

Fishery resource managers have expressed the view that summer low flows and high water temperatures in the mainstem Green River are a significant issue to habitat quantity and quality, and that protection and restoration of river inflows are essential. The new instream flow guarantee associated with Tacoma's second diversion water right will provide some protection and should prevent recurrences of record low flows as have been experienced in the past. In the low flow month of September, for example, the 7-day low flow in the Green River at Auburn under current conditions has been less than 209 cfs in about 10% of all years. Under the new operating procedures, the 7-day low flow will be guaranteed to not drop below 225 cfs and is expected to be maintained at or above 250 cfs in 90% of all years.

The new instream flow obligations and guarantees do not affect flows in the streams which are tributaries to the Green. They do, however, ensure that future Green River low flows at the Auburn control point will be largely independent of (and unaffected by) changes to the flow regimes of the upstream tributaries. For example, the flow obligations would require additional releases from the storage pool to offset any future reduction in tributary low flows. If the tributary low flows should be increased or improved, there could be a corresponding reduction in flow releases from the storage pool. The current study quantifies the flows in the tributary streams, but does not include fish habitat or biological assessments of the adequacy of those flows. If management actions are taken to improve low flows in the tributary streams, the flow benefits will be limited to the tributary channels and will likely not extend to the mainstem channel.

The new instream flow obligations and guarantees will similarly ensure that future Green River low flows will be largely independent of (and unaffected by) changes to groundwater interactions upstream of the Auburn gage. Prior work has identified two reaches along the Green River with significant, concentrated groundwater inputs. The first is in the vicinity of Auburn, where substantial quantities of groundwater from the adjoining White River basin (WRIA 10) flow to aquifers connected to the Green River. The second reach extends from RM 48 to RM 52, where several large springs flow into the Green River. These springs, which include Icy Creek, Black Diamond and Palmer Springs, are believed to be the discharge points from the adjacent Coal Creek and Deep Creek closed depression basins. Groundwater inputs are perceived by resource managers as being important sources of the cool, clean water which is essential for fish habitat.

Land use activities can have a direct and sometimes dramatic impact on streamflows. An assessment was made of the existing and planned urbanization within the study area to provide an indicator of potential past and future impacts to groundwater recharge and streamflows. The analysis does not specifically quantify the effects of land use activities on streamflows and temperatures but does provide data which are relevant to such an analysis. The lower portion of the study area is already heavily urbanized, with the Soos, Jenkins, and Mill Creek (Auburn) sub-basins all having more than 30% impervious cover. A land use change analysis based on satellite imagery of current conditions and land use zoning to predict future conditions found that 18.5 square miles of new urban-density development is planned for areas that are presently covered with forest, grass or bare soil. Approximately one half of this new development is planned to occur in the Soos Creek basin including its tributaries, Jenkins and Covington Creeks.

Water management activities can also have a direct and sometimes dramatic impact on streamflows. An assessment was made of the total extraction (withdrawals) and the total net water exports from the basin above each flow analysis point. Water extraction in the study area is dominated by several large public water supply systems which include Tacoma Water, Covington Water District, and the Cities of Auburn, Black Diamond, Enumclaw, and Kent. For these and other specific users which were identifiable from Department of Health and Department of Ecology records, actual source-specific monthly withdrawal data were obtained for calendar year 2000 and aggregated by sub-watershed. Withdrawals for self-supplied domestic, irrigation, commercial, and other uses were estimated. Potable water exports (wholesale water sales) between utilities were estimated from differences in each utility's Year 2000 Average Day Demand as reported in the Puget Sound Water Supply Outlook and the reported Year 2000 source withdrawals. Wastewater exports from each of the study basins were estimated from modeling performed by the King County Wastewater Treatment Division.

A comparison of the managed water fluxes to the current condition streamflows found that managed water impacts are discernable in all study basins. The largest impacts occur, expectedly, during low flow conditions. The greatest impacts are in Covington Creek, then in Jenkins Creek, which are both tributaries to Soos Creek which ranks third. On Covington Creek, the analysis suggests that extractions and exports have, in combination, caused the natural-conditions median monthly flow in August and 7-day low flows to be depleted by about 70% and 90% respectively. A net depletion of the flow in the middle and lower Green River is also apparent, with extraction and export amounts ranging from about 10% of the total annual flow in 2000 to about 40% of the 7-day low flows. Of the studied streams, the least affected is Newaukum Creek for which extraction and export amounts are equivalent to about 6% of the mean annual flow in 2000 and about 20% of the 7-day low flows.

Eight alternative management actions are presented to stimulate discussion and consideration of options for improving water quantity conditions for fish. These include: (1) land cover management of impervious surfaces and forest areas, (2) various water supply management techniques, (3) stream morphology hydraulic restoration, (4) stormwater infiltration, (5) drought preparedness planning, (6) preservation of functioning septic systems, (7) use of reclaimed wastewater, and (8) additional agreements with Tacoma Water. These options could be pursued to varying degrees alone or in combination in different geographic areas or sub-basins. No single action will solve the water quantity problems that salmonids face in particular sub-basins or in specific years.

It is hoped that further work will take the next step of identifying specific reaches and time periods for which achievable changes in available water quantity would perceptibly benefit or harm fish populations. Such specificity will facilitate reasonable consideration of potential targeted actions to protect and improve flows at those locations and times, and to cumulatively yield significant benefits for salmonids in the Green River and its tributaries.

Contents

List of Tables

List of Figures

Acknowledgements and Credits

This work was performed by Northwest Hydraulic Consultants (NHC) as a subconsultant to Anchor Environmental. Lorin Reinelt of King County DNRP was the King County project manager and provided technical and administrative liaison with the WRIA 9 Technical Committee. Bill Rozeboom, PE, was the NHC project manager and coordinated the contributions from NHC, King County, Ecology, and sub-consultant staff.

The work presented in this document was accomplished with significant technical contributions from King County and Ecology staff. Contributions by King County staff included background document retrieval and preparation of base maps (Karen Bergeron); retrieval and interpretation of well data plus informed advice on local groundwater issues (Ken Johnson); statistical analysis of flow data for tributary streams (Jeff Burkey); processing and interpretation of wastewater flow model results (Mark Lampard); and preparation of report sections on Normative Flows, and Alternative Management Actions for Water Quantity (Lorin Reinelt). The report section on Fisheries Perspective Assessment of Existing Streamflows was prepared by King County (Karen Bergeron and Lorin Reinelt) in consultation with Fish and Wildlife (Gary Engman). Contributions by Ecology staff included obtaining recent metered water withdrawal data from major water utilities (Arlene Harris), and assessments of non-municipal water rights and exempt wells (Steve Hirschey).

Bill Rozeboom of NHC was the primary author of this report. Supporting Mr. Rozeboom in this work were NHC staff members David Hartley who provided broad technical guidance, Derek Stuart who conducted the GIS-based analyses of land cover, zoning, water withdrawal, and census data, Rita Bout who provided drafting support, and Jim Mathieu of Northwest Land and Water who performed the assessments of significant groundwater inputs and hydraulic continuity. Larry Karpack of NHC provided quality assurance review of the work products.

1 Introduction

This report documents an assessment of current water quantity conditions in the Green River Basin, performed as Task 3.3 of the WRIA 9 Strategic Assessment. The study area for the work is all portions of the Green River Basin which are upstream from River Mile 23.8. That lower boundary was established to be just downstream from where Mill Creek (Auburn), the last of the basin's major freely-draining tributaries, enters the Green. In the context of the large Green/Duwamish sub-basins described in other studies, this study area for this work focuses on the upper Lower Green, the Middle Green, and the Upper Green River sub-watersheds.

Figure 1.1 provides a location map showing the boundaries of the study area and the sub-basins addressed in the analysis.

The assessment focuses on identification and characterization of significant surface and groundwater linkages and inputs to the upper Lower, Middle, and Upper Green River and provides a coarse water budget for people and fish in the study area. The technical work was performed in the broader policy context of identifying opportunities to manage water resources and to limit degradation of important sources of cool, clean water in the Green River.

Conceptual Approach

The conceptual approach for the water quantity assessment is to use best available information to quantify: (1) the streamflows which currently exist at representative points of interest; (2) the geographic extent of surface topography and groundwater basins tributary to those points; (3) the current state of basin land development (basin imperviousness) above those points; and (4) current significant consumptive water withdrawals from those basins. The assessment also compiles best available information to quantify: (5) the currently-authorized basin land use development above each point; and (6) the currently-authorized significant water withdrawals from those same basins. Items (5) and (6) incorporated currently-approved land use zoning and currently-certificated or approved water rights and represent a "do nothing" scenario of future conditions.

The assessment does not attempt to re-create any "natural" flows which would have existed in pristine basins without human intervention. Instead, the focus of the study is on actual streamflows which reflect current conditions, and characterizes those flows using hydrologic statistics which are meaningful to fish utilization and water balance assessments. The study also compiles information to qualitatively assess whether basin buildout to currently-authorized land uses and full utilization of existing water rights/certificates is likely to cause significant changes to the current streamflows. The results of these assessments are used as the foundation for identifying water management opportunities.

Analysis Points and Sub-Basins

Twelve sub-basins and twelve corresponding streamflow analysis points were identified for this study in consultation with the WRIA 9 Technical Committee. The analysis points correspond to the locations of active stream gages on the mainstem Green River, stream gages near the mouths of major tributaries, and the mainstem channel at major tributaries and at some intermediate points. Analysis points are located at the downstream end of each of the study sub-basin areas shown on Figure 1.1. The analysis points are described further in Chapter 3.

Analysis Statistics

The analysis statistics selected for the current work were chosen in the narrow context of managing water for both fish and people. Streamflow statistics that emphasize low-flow conditions were chosen because low flows can be a limiting factor to fish utilization of streams. It is during low flows that competition for water between fish and for people becomes most critical. The statistics also include average-flow conditions because average flows are relevant to a water balance budget in which some storage is available and which evaluates water supplies and demands over monthly and annual time frames. Additional, complex flow statistics are expected to be produced later as a product of the King County Normative Flow Studies project, in progress.

The analysis statistics selected to describe current conditions streamflows for each of the analysis points are listed below.

1. 7-day low flows, by month, long-term medians (50% exceedance).
2. 7-day low flows, by month, 90% exceedance values.
3. Mean monthly flows, long-term medians (50% exceedance).
4. Mean monthly flows, 90% exceedance values.

The analysis statistics selected to describe land use and water extraction conditions in the sub-basins tributary to each point of analysis are listed below.

5. Current-conditions consumptive extraction from wells and diversions.
6. Future-conditions potential cumulative extraction based on outstanding water rights certificates and claims for major urban purveyors.
7. Current conditions effective impervious area, from satellite imagery.
8. Future conditions effective impervious area per approved land-use zoning.

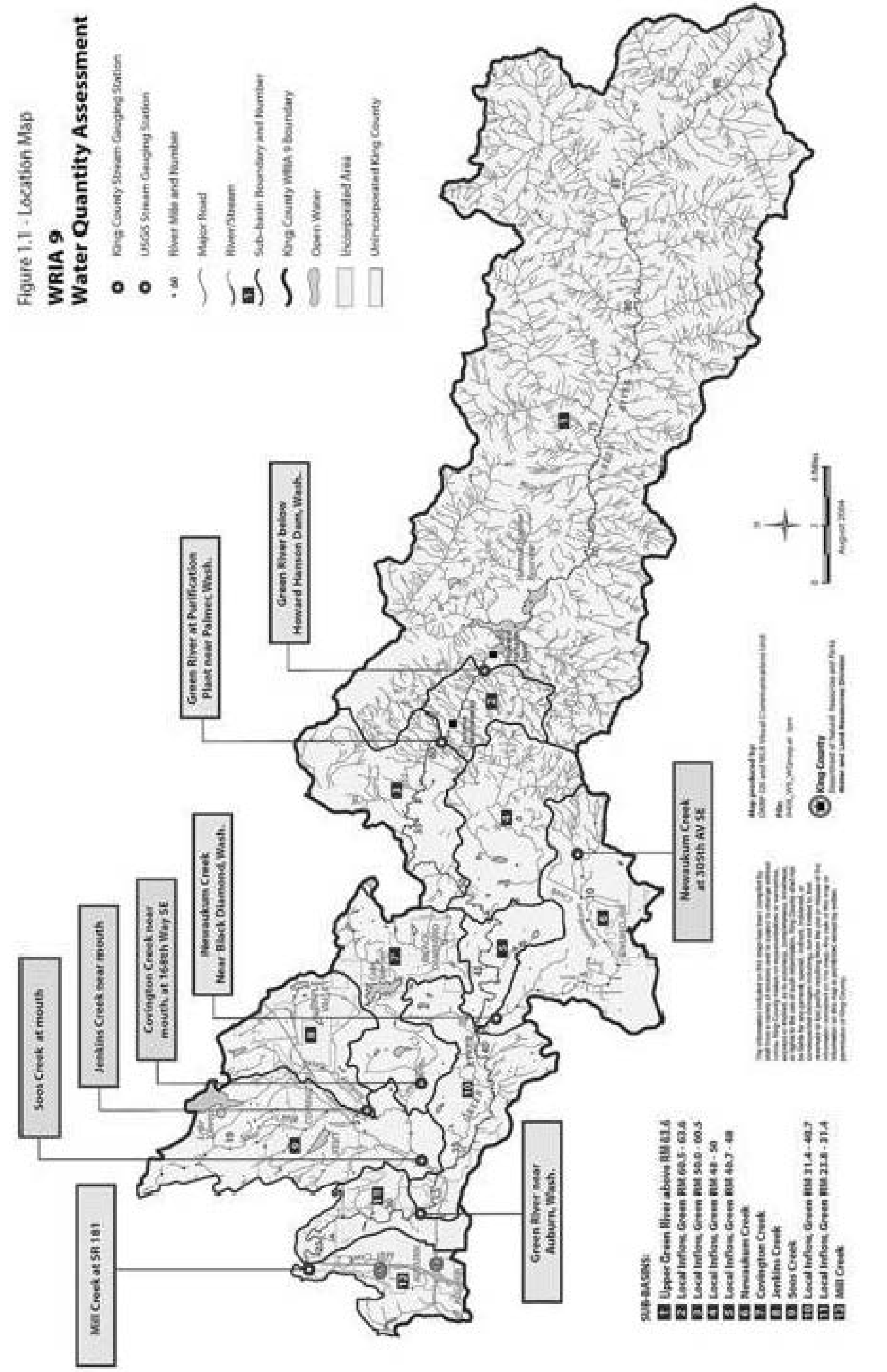


Figure 1.1. Location Map (Placeholder for 11 x 17 color sheet)

2 Summary Inventory of Existing Information

A large body of information exists to describe surface and ground water resources and fish populations in the Green River Study Area. Additional studies by others are currently in progress to expand that body of knowledge. The current work draws from the existing information base and, to the extent possible, is coordinated with other known active studies. The intent is to not re-create (or ignore) relevant information from previous work, and to not duplicate the products of other efforts in progress.

A summary list of active studies, published reports, and sources of data which were obtained for review is provided below. A CD accompanying this report provides digital copies of those reports obtained digitally from internet or agency sources. Most of the older reports, including groundwater studies and water supply plans, are published only in hard-copy format and were obtained for review as loan copies from King County and Ecology libraries.

Information Source	**Date**	**Contents**	**Availability**
Habitat Limiting Factors and Reconnaissance Assessment Report, Green/Duwamish and Central Puget Sound Watersheds, by King County and Washington Conservation Commission	12/2000	Major reference. Provides a current snapshot in time of the existing salmonid species and the habitat conditions that limit the natural production of salmonids in the Green / Duwamish River watershed and other areas within WRIA 9.	Digital (copy included on CD)
Tacoma Water Habitat Conservation Plan Green River Water Supply Operations and Watershed Protection	07/2001	Major reference. Documents current, and proposed upper basin withdrawals, negotiated instream flow guidelines, and discusses operations of Howard Hanson Dam.	Digital (copy included on CD)
2001 Central Puget Sound Regional Water Supply Outlook, by the Central Puget Sound Water Suppliers' Forum	07/2001	Major reference. Assesses the state of municipal water supply and preliminary aquatic habitat instream flow needs in the three-county region of Pierce, Snohomish, and King Counties.	Digital (copy included on CD)
US Geological Survey Continuous Daily Streamflow Data	Annual	Recorded streamflow data at 42 mainstem and tributary sites in the Green-Duwamish basin, various periods of record.	CD includes station list, with links to on-line data.
King County WRIA 9 Streamflow Data	Annual (recent)	Recorded recent streamflow data for many tributary streams.	King County DNR
City of Auburn 1999 Hydrogeologic Characterization Report	1999	Four-volume report includes groundwater modeling and non-USGS streamflow data for sites on the Green and White Rivers in the vicinity of Auburn	Excerpts scanned as PDF file, included on CD.

Information Source	**Date**	**Contents**	**Availability**
Ecology Initial Watershed Assessment, WRIAs 9 & 10	01/1995	Provides an overview of basin hydrology, instream flow regulations, and consumptive use patterns	Digital (copies included on CD)
USGS Water Use Data Summary by Hydrologic Unit	1985, 1990, 1995	Total annual water use, aggregated by groundwater vs surface water source, and type of use,	Digital (1995 data included on CD)
Ecology, Green River Fish Habitat Analysis using the Instream Flow Incremental Methodology	07/1989	Five study sites were analyzed representing approximately 40 miles of the Green River, excluding RM 0 to 12 (tidal influence) and also excluding the gorge from RM 46 to 58.	Digital (copy included on CD)
USGS Water Supply Paper 1852, Water Resources of King County, Washington	1968	Good summary of surface water and groundwater resources, availability, and water use.	Scanned copy included as PDF file on CD
USGS Water Supply Bulletin No. 28, Geology and Ground-Water Resources of Southwestern King County	1969	Good documentation of geology and groundwater. Includes estimates of groundwater flows and summary of known springs.	Excerpts scanned as PDF file, included on CD.
South King County Ground Water Management Plan	04/1991	Includes maps of groundwater flow in shallow aquifer system; analyses of groundwater in Green River Valley and in Covington upland (Soos, Jenkins, Covington Creeks) .	Excerpts scanned as PDF file, included on CD.
USGS Water-Resources Investigations Report 92-4098, Occurrence and Quality of Ground Water in Southwestern King County	1995	Most recent and detailed mapping of aquifers. GIS layers with report's spring locations and major wells obtained for this study from Steve Sumioka (USGS)	Excerpts scanned as PDF file, included on CD.
Directory to Washington State Coal Mine Map Collection	1983	Discusses mining methods, shows areas of know coal mines, but no detail. Mines documented in area of Deep Creek, Coal Creek sub-basins.	Excerpts scanned as PDF file, included on CD
King County Regional Infiltration/Inflow (I/I) Control Program, wet weather monitoring	2001-2002	Data and technical memos. Very large amounts of detailed data focusing on wet-weather, not low flow, periods.	Tech Memos included on CD
City of Kent Water System Plan	1988	Water sources include Clark, Kent, and Armstrong Springs, plus wells and interties to Water District 75 and Tukwila.	Excerpts scanned as PDF file, included on CD.

Information Source	Date	Contents	Availability
Covington Water District Comprehensive Water System Plan	1994	Water sources include wells or well fields at Ravensdale, Lake Sawyer, and Witte Road, with other wells applications pending. Interties with Cedar River Water and Sewer, and Water District No. 111.	Excerpts scanned as PDF file, included on CD.
Soos Creek Water and Sewer District Water Comprehensive Plan	1996	Water is purchased from the City of Seattle. The district uses water diverted from the Cedar River to the Lake Youngs reservoir.	Excerpts scanned as PDF file, included on CD.
City of Auburn Comprehensive Water Plan	2001	Water sources include springs tributary to the White River and several wells in aquifers associated with the White and Green Rivers. Interties to adjacent purveyors	Excerpts scanned as PDF file, included on CD.
City of Enumclaw 1993 Comprehensive Water System Plan	05/1994	Water sources include two wells (one as a standby source) and two springs. An intertie to Tacoma is available for emergency use.	Excerpts scanned as PDF file, included on CD.
City of Black Diamond Final Comprehensive Water System Plan	2000	Water source is a series of four springs: the South Springs, Middle Springs, North Springs, and Palmer Springs. They are located high on the south bank of the Green River and are collectively known as the Black Diamond Springs.	Excerpts scanned as PDF file, included on CD.
Water District No. 111 of King County Water System Comprehensive Plan	1997	Base water supply provided by an intertie to the City of Auburn Lea Hill reservoir. District uses six of its own eight wells to augment supply.	Excerpts scanned as PDF file, included on CD.
Various HSPF models for tributary basins	2004	Models are being developed by King County for a water quality assessment of the Green-Duwamish Basin.	King County DNR
Spreadsheet model of mainstem Green River after diversion and management scenarios	2004	Modeling of the mainstem Green River was performed by CH2M Hill for Tacoma Water's Habitat Conservation Plan	Simulated future flows included on CD
Monthly water use extraction data from major purveyors, by source	recent	Recently monthly water extraction by major municipal users obtained by Ecology.	Included on CD
Water rights certificates, permits, and claims	current	Location information to nearest section. Actual use status unknown	Included on CD

3 Current Condition Streamflows

3.1 Methods and Approach

The approach for the water quantity assessment is to use actual flow data where available to quantify current streamflow conditions at representative points of interest. The focus of this effort is on low flows, which are potentially a limiting factor for fish habitat, and monthly average flows, which reflect total basin runoff and water availability. Current conditions streamflows are intended to represent the flow regimes of about years 2001-2002, corresponding to the most recent basin land use analyses and recorded streamflow data available for assessment. However, because statistical analysis methods require an extended record of flows, the current conditions results are more realistically associated with land use and water extraction practices over the past decade.

The flow regime on the mainstem Green River is expected to significantly change from current (2001-2002) conditions as a result of the forthcoming implementation of the City of Tacoma's[1] second diversion water right. The exercising of that water right is scheduled to begin in the spring of 2005 and will mark the beginning of revised flow management practices for the mainstem Green River. Those revised practices include increased withdrawals combined with additional water storage capacity and new instream flow regulations. To recognize this change in river management procedures, a second set of flows statistics reflecting the anticipated future flow regime is developed for analysis points on the mainstem Green River. These "future" flows may be more representative of near term future flows than those determined for current conditions.

The scope of this study does not include estimation of the flows that would have existed in the basin under a natural condition without human effects. The focus is on current conditions streamflows which can be described with a high level of certainty based on recorded flow data and the results of simulation models calibrated to recorded flow data.

Different methods were used to define current conditions streamflows for the mainstem river versus flows in the major tributaries to the Lower/Middle Green River. Flows in the mainstem are significantly influenced by storage at Howard Hanson Dam (HHD) and by City of Tacoma water supply withdrawals. Flows in the major tributaries to the Lower/Middle Green River are not affected by flood control operations but are significantly influenced by urbanization effects including land cover alteration and water use. Flow regimes in both the main channel and the tributary streams have changed over time, coincident with increasing basin development and evolving water management practices.

The methods used to characterize current conditions are described below.

- Current conditions streamflows for the mainstem Green River were determined by a direct analysis of streamflows recorded by the USGS from 1964 to 2002. This corresponds to the period in which Howard Hanson Dam, a flood control facility operated by the US Army Corps of Engineers, has been in operation. River flow management practices (e.g. reservoir operations, water supply withdrawals, etc.) have evolved over this period, and consideration was given to adjusting the historical data to reflect the most current practices. However, no adjustments were made due to available resources and the need to also assess a flow scenario to incorporate the

[1] Water supply for the City of Tacoma is provided by Tacoma Water. Tacoma Water is one of three operating divisions of Tacoma Public Utilities, owned by the City. In this report, references to Tacoma, Tacoma Water, Tacoma Public Utilities, and to the City of Tacoma are used interchangeably.

anticipated effects of the City of Tacoma's second diversion water withdrawals, scheduled to begin in spring 2005.

- "Future" conditions streamflows for the mainstem Green River were determined using simulated flow data developed for the Environmental Impact Statement and Habitat Conservation Plan for the Tacoma Water second diversion water supply project. The simulated flow data were obtained from CH2M Hill with Tacoma Water authorization and consist of Green River daily flows for the period 1964 through 1995, adjusted for the effects of the second diversion project, the Howard Hanson Dam Additional Water Storage project, and accompanying instream flow commitments from a 1995 agreement between the Muckleshoot Indian Tribe and the City of Tacoma[2].

- Current conditions streamflows for the major Lower/Middle Green River tributaries were initially determined using data generated with HSPF simulation models calibrated to recently-collected streamflow data. The HSPF models were used to simulate continuous flow hydrographs for the 50-year period from 1948 through 1998, based on the model calibration to current conditions. However, due to model emphasis on storm runoff events and relatively poor calibration to low flows, this approach was largely abandoned in favor of a direct evaluation of the available streamflow data recorded since 1988.

Flow characteristics were evaluated for the twelve sites listed in Table 3.1. These include seven sites on the mainstem Green River, and five sites on significant tributaries to the Lower/Middle Green. The tributaries are Mill, Soos, and Newaukum Creeks which discharge to the Green River, and Jenkins and Covington Creeks which are part of the Soos Creek basin. Figure 1.1 shows the basin areas upstream of each of the twelve analysis points.

Table 3.1
Streamflow Analysis Points and Year 2000 Mean Flows

Analysis Point	River Mile	Tributary Basins	Basin Area Sq. Mi.	Year 2000 Mean Flow, cfs
MAINSTEM CHANNEL				
Green River below HHD (USGS Gage 12105900)	63.6	1	222	753 (1)
Green River near Palmer (USGS Gage 12106700)	60.5	1-2	231	687 (1)
Green River in Gorge	50.0	1-3	253	732 (3)
Green River below Icy Creek Springs	48.0	1-4	275	775 (3)
Green River below Newaukum Creek	40.7	1-6	310	847 (3)
Green River near Auburn (USGS Gage 12113000)	31.4	1-10	397	1,021 (1)
Green River below Mill Creek	23.8	1-12	419	1,066 (3)
MAJOR TRIBUTARIES TO LOWER/MIDDLE GREEN				
Newaukum Creek near Black Diamond	0.9	6	27.1	47 (1)
Covington Creek nr Mouth (Soos RM 2.9 tributary)	1.2	7	21.5	25 (2)
Jenkins Creek nr Mouth (Soos RM 4.1 tributary)	0.4	8	15.9	30 (2)
Soos Creek near Mouth	1.1	7-9	66.3	95 (1)
Mill Creek at SR 181 (near Mouth)	0.3	12	12.3	17 (4)

Source of flow data: (1) USGS Gage; (2) King County Gage; (3) Interpolated Value; (4) HSPF Simulation

[2] Details of the instream flow requirements under the 1995 agreement are presented in Section 3.2.2.

3.2 Mainstem Green River

Green River flows have been significantly altered by past and ongoing human activities including major diversions, consumptive withdrawals, and flood control activities. For context, brief summaries of these activities are provided below.[3] Flow statistics are provided following the summaries of major historical alterations and a description of Green River flow management activities by Tacoma Water and the US Army Corps of Engineers.

3.2.1 Chronology of Major Alterations

Significant historical changes to the Green River basin include the events summarized below.

- 1851: European settlement begins in the Duwamish River. Prior to settlement, the Green River was tributary to the White River, and the Duwamish River began at the confluence of the White River and the Black River at Duwamish (Green) River Mile 11.
- 1906-1911: White River is diverted from the Duwamish Basin to the Puyallup River, reducing the Green River watershed area by 30 percent. The original confluence of the White and Green Rivers was near Auburn. Under current conditions some groundwater flow from the White River basin continues to discharge to shallow aquifer of the Green River valley in the vicinity of Auburn (at about RM 35). The groundwater flow is intercepted by the Green River and converted to surface flow along a channel reach extending approximately from upstream of Auburn at RM 35 to the Mill Creek confluence at RM 23.
- 1913: City of Tacoma begins diverting water from the Green River to provide water for homes and industry. Anadromous salmonids blocked from Upper Green River sub-watershed since 1911 when construction for the diversion began.
- 1912-1916: Black and Cedar Rivers are diverted from the Duwamish Basin to Lake Washington to improve navigation, further reducing watershed area by 40 percent from its original size. The original confluence of the Black and Green Rivers was near Renton at Green River RM 11. Under current conditions, Springbrook Creek drains to the remnant Black River channel and thence to the Green River.
- 1962: Howard Hanson Dam is completed for flood control purposes.
- 1895-1980: The Green/Duwamish River is channelized and diked for navigation and flood control.
- 1945-2000: Residential, commercial, and industrial land uses expand, largely replacing farmlands and forests in the western half of the Green-Duwamish Watershed.
- 2005: Tacoma Water (Tacoma Public Utilities, City of Tacoma) plans to first exercise its second diversion water right, triggering new instream flow obligations.

3.2.2 City of Tacoma Withdrawals

Surface water is diverted from the middle Green River basin for municipal supply by the City of Tacoma, which is the principal consumptive user of water from the mainstem Green River. In 1906 and 1908, the City of Tacoma filed water right claims on the Green River for future withdrawals of 400 cfs . In 1911, Tacoma began construction of a water diversion dam at RM 61 on the Green River. In 1913, construction

---

[3] The summaries provided here draw heavily on direct text excerpts from the 1995 Ecology WRIA 9 Initial Watershed Assessment, the 2000 WRIA 9 Habitat Limiting Factors and Reconnaissance Assessment Report, and the 2001 Tacoma Water Habitat Conservation Plan. Digital copies of those documents in their entirety are included on the CD which accompanies this report.

of a pipeline with a capacity of 65 cfs was completed. By 1952, pipeline capacity had been increased to 113 cfs as the pipeline was upgraded over the years. The existing pipeline is operated under Tacoma's First Diversion Water Right Claim (FDWRC)[4]. Water is continually diverted from the mainstem Green River except at times of excessive turbidity (>5 NTUs), when Tacoma uses groundwater pumped from its North Fork Green River well fields located upstream of Howard Hanson Dam and well fields located in South Tacoma.

In 1985, Tacoma was granted a Second Diversion Water Right (SDWR) to an additional 100 cfs. Water available under the SDWR is scheduled to first be utilized in spring 2005, subject to restrictions described in Tacoma's 2001 Final Habitat Conservation Plan which includes a 1995 agreement between the Muckleshoot Indian Tribe and the City of Tacoma.

Tacoma's FDWRC is not constrained by Washington State minimum instream flow requirements because the asserted water right represented by its claim predates Ecology's adoption of the basin's instream flow rules. However, in recent years, Tacoma has voluntarily cooperated with other agencies and groups to minimize impacts of water withdrawals on fisheries and other instream resources.

Tacoma's Second Diversion Water Right (SDWR) is subject to State-imposed minimum instream flows at the USGS gage at Palmer. Additional constraints come from a 1995 agreement between the Muckleshoot Indian Tribe (MIT) and Tacoma Public Utilities. The agreement with MIT provides that upon first exercising of the SDWR, Tacoma's FDWRC will be constrained by a commitment to support instream flow levels measured at the USGS gage at Auburn.

Instream flow excerpts from the 1995 MIT/TPU agreement are reproduced below. State-imposed regulatory instream flows for the Green River at Auburn and at Palmer were filed in June 1980 and are published in chapter 173-509 Washington Administrative Code (WAC). As a general rule, regulatory instream flows do not represent the flows which are necessarily achieved in the river, but rather establish flow thresholds at which consumptive water withdrawals by junior (interruptible) water right holders must cease. Water rights issued prior to the adoption of instream flow regulations are senior to, and are normally exempt from, the instream flow regulations.

It should be noted that the above MIT/TPU agreement pre-dates and does not address the effects of the joint USACE and Tacoma HHD Additional Water Storage (AWS) project. That project and its effects are discussed in Section 3.2.3 which follows.

[4] In 1971, a water right claim of 400 cfs was filed by Tacoma for this diversion. Under current conditions, Tacoma withdraws up to 113 cfs under its FDWRC. A water right claim on file with the Washington State Department of Ecology (Ecology) cannot be validated until an adjudication occurs. As part of its Habitat Conservation Plan, Tacoma will not pursue adjudication of the full 400 cfs, but will voluntarily cap its FDWRC at 113 cfs

AGREEMENT BETWEEN
THE MUCKLESHOOT INDIAN TRIBE
AND
THE CITY OF TACOMA
REGARDING THE GREEN/DUWAMISH RIVER SYSTEM
1995
(Section 2 presented to describe instream flow commitments.)

SECTION 2. INSTREAM FLOWS

2.1 Guaranteed Minimum Instream Flow Levels That Vary With Annual Conditions

TPU shall provide the following guaranteed minimum continuous instream flows, which will vary with weather conditions during the summer months, in the Green River as measured at the Auburn Gage. For Wet Years the minimum continuous instream flow shall be 350 cfs. For Wet to Average Years[5] the minimum continuous instream flow shall be 300 cfs. For Average to Dry Years the minimum continuous instream flow shall be 250 cfs. For Drought Years, the minimum continuous instream flow shall range from 250 to 225 cfs, depending on the severity of the drought. Before any decision to drop instream flows from 250 cfs to 225 cfs (as measured at the Auburn Gage), consultation among the Resource Agencies, MIT, the Corps of Engineers, and TPU shall explore alternatives to lowering the minimum continuous instream flow, and TPU shall comply with the requirement of Section 2.6[6] of this Agreement.

2.2 Instream Flow Levels for Second Diversion

TPU shall meet the continuous instream flow requirements identified in Sections 2.2.1 and 2.2.2 whenever it is withdrawing water from the Green River with its Second Diversion. TPU shall meet both sets of instream flow requirements before it can withdraw any water with its Second Diversion. To the extent that these instream flow requirements are greater than the State Instream Flows, these instream flow requirements control.

2.2.1 Instream Flow Requirements for Palmer Gage

TPU shall meet the following continuous instream flow requirements, as measured at the Palmer Gage, as a condition of withdrawing water from the Green River with its Second Diversion. From July 15 to September 15 of each year the continuous instream flow level shall be 200 cfs. From September 16 to October 31 of each year the continuous instream flow level shall be 300 cfs. For all other days of the year (November 1 to July 14), the continuous instream flow level shall be 300 cfs, which is the same as the State Instream Flows for those days.

[5] Wet, average, dry, and drought weather conditions are to be determined by conditions within Howard Hanson Reservoir, considering the date and the current volume of water stored within the 24,200-acre-foot block of water for flow augmentation purposes. Details are presented in the Tacoma HCP under Section 5.1.1: Habitat Conservation Measure: HCM 1-01 FDWRC Instream Flow Commitment. The rule curves to determine weather conditions are per HCP Figure 5.1 which is reproduced at the end of this text box.

[6] Section 2.6 is titled "Water Use Curtailment by TPU."

2.2.2 Instream Flow Requirements for Auburn Gage

In addition to the instream flow requirements of Section 2.2.1, from July 15 to September 15 of each year, TPU shall meet the continuous instream flow requirement of 400 cfs, as measured at the Auburn Gage, as a condition of withdrawing water from the Green River with its Second Diversion. TPU specifically understands that if instream flows at the Auburn Gage fall below 400 cfs during the referenced period, the Second Diversion may not be used even if the instream flow requirements in Section 2.2.1 are being met.

Reservoir storage criteria for determining weather conditions: (HCP Figure 5.1)

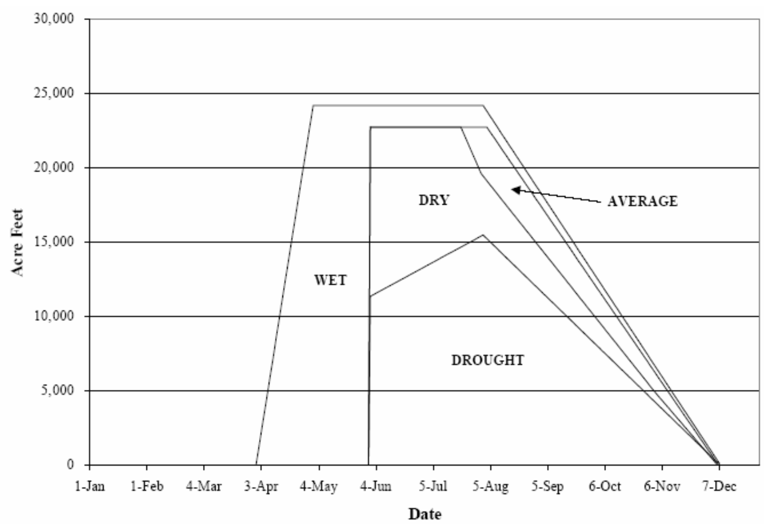


Figure 5-1. Storage reference zones within Howard Hanson Reservoir used to determine minimum flow conditions under yearly wet, average, dry and drought conditions during the period 15 July to 15 September. The storage reference zones pertain to the 24,200-acre-foot block of water stored for flow augmentation purposes.

3.2.3 Flow Management at Howard Hanson Dam

Howard Hanson Dam (HHD) is a federally funded and operated project on the Green River at RM 64.5, authorized by Congress for flood control and conservation storage. The conservation storage is used to augment low summer/fall flows for fisheries enhancement. Dam construction began in February 1959, and reservoir filling began in December 1961. No upstream fish passage facilities were originally incorporated into HHD because it was located approximately 3.5 miles upstream from Tacoma's Headworks Diversion Dam which had blocked upstream fish passage since 1913. Fish utilization of the upper basin is expected to be restored through several measures in the HCP. Those measures include constructing a fish ladder and adult collection and trap-and-haul facility at the Tacoma Diversion to provide passage to adult fish around the Headworks and HHD.

The U. S. Army Corps of Engineers (USACE) operates the dam to prevent flood flows over 12,000 cfs at the Auburn gage and to provide a minimum discharge of 223 cfs from the dam to ensure that 110 cfs passes the Palmer gage after diversion of up to 113 cfs by Tacoma Water. The conservation storage operation of the dam involves capturing late winter and spring runoff and augmenting low flows in July, August, September, and October. The original design and operation of the project provides for 24,200 ac-ft of water storage to augment low flows. The project operation was subsequently modified in the 1990s to provide an additional 5,000 ac-ft of stored water for fisheries benefits, this being one element of a planned Additional Water Storage (AWS) project.

Additional storage and flow management aspects of the AWS project are proposed as Habitat Conservation Measure 2-02 of the Tacoma Water HCP. Under this HCP proposal, authorized uses of HHD will be expanded to provide up to 20,000 ac-ft of additional stored water for municipal and industrial use. The additional storage for the AWS project will be obtained by increasing the reservoir water level during spring and summer months when the space is not required for flood control purposes. Water will be added to the municipal storage pool under Tacoma's Second Diversion Water Right at a maximum rate of 100 cfs, subject to instream flow commitments at the time the water is stored. Water withdrawals from the municipal storage pool will be made when needed by Tacoma Water and will be exempt from further instream flow restrictions at the time of withdrawal.

Reservoir operation at HHD has evolved over time to recognize and address a variety of resource needs. A summary of past operational practices may be found in Chapter 5 of Tacoma Water's HCP. HHD reservoir operation by the USACE currently involves frequent communication with members of the Green River Flow Management Committee. This interagency committee was formed in 1987 and consists of representatives from MIT, State, Federal, and county resource agencies, and other groups. The USACE considers input from the group in an adaptive management strategy to adjust the refill and release regime based on a short-term planning horizon.

Releases from HHD are adjusted to account for changing inflow and weather conditions to provide additional flows to benefit fisheries resources, with consideration for whitewater recreational opportunities and specific community activities[7]. Adjustments in the timing and rate of spring refill represent a compromise between juvenile outmigrant passage through HHD reservoir and downstream fisheries impacts. The refill strategy attempts to provide flows for steelhead spawning and incubation in response to expected weather and runoff conditions.

3.2.4 Flow Statistics

Flow statistics were determined for a total of six sites on the mainstem Green River from River Mile 63.6, just below Howard Hanson Dam, to River Mile 23.8, just below the confluence with Mill Creek (Auburn). The sites were selected to correspond to the locations of active USGS stream gages and major tributary inputs. The downstream end of the studied reach was selected in consultation with the WRIA 9 Technical Committee so as to concentrate the study resources in those reaches of the Lower/Middle Green above the zone of tidal influence and of greatest interest for fish utilization.

The flow statistics are based on historical and simulated flows for USGS gage sites below Howard Hanson Dam (USGS 12105900), at the Purification Plant near Palmer (USGS 12106700), and near Auburn (USGS 12113000). The statistics representing current conditions are based on the daily flow data published by the USGS for these sites for the period January 1964 through September 2002. The statistics representing future conditions are based on daily flow simulation data provided by Tacoma Water for these same sites for the period January 1964 through December 1995. The future flow data represent full exercising of Tacoma's Second Diversion Water Right in combination with the implementation of the Additional Water Storage Project and adherence to all applicable instream flow commitments.

---

[7] U.S. Army Corps of Engineers (USACE). 1995. Howard Hanson Dam draft environmental impact statement for operation and maintenance.

Daily flows for other sites were estimated by linear interpolation of same-day flows at the Palmer and Auburn gages, based on basin area. The sites near Palmer and Auburn are significant both for data availability and because they are control points for instream flow regulations. The difference between same-day flows at Palmer and Auburn reflect the combination of local inflows and channel routing effects. Local inflows are the cumulative surface and groundwater inputs from tributary streams and basins (e.g. flows from Icy Creek Springs and Newaukum Creek). Channel routing effects include flow travel time and the volume of water going into and out of channel and floodplain storage during periods of rising and falling stages. The methods used by Tacoma Water to evaluate future flows under the SDWR did not specifically address routing effects. As a simplifying assumption, the SDWR evaluations assumed that the incremental flows between Palmer and Auburn for the simulation period were identical to historical incremental flows except for negative incremental flows which were treated as zero values.

During periods of rapidly rising flow, about 6 days per year on average, daily flows at Auburn are less than those at Palmer because channel routing effects (i.e. water put into storage) are greater than local inflows. By ignoring such negative incremental flows, the future condition modeling slightly exaggerates the total annual volumes of local inflow below Palmer. The modeling also fails to adjust the computed local inflows for the very different channel routing effects which will occur during spring months once the Additional Water Storage project is operational and is storing the spring freshets. These model limitations are noted but should not adversely affect the overall model results. Significant channel routing effects would be most closely associated with flood periods when low streamflows would not limit Tacoma withdrawals.

Tables 3.2 to 3.8 below present the flow statistics computed for the mainstem Green River for current and future conditions. Monthly flow statistics were determined by computing the mean monthly discharge and the 7-day low flow for each month of record and then sorting the data. On average, 50% exceedance (or median) values are exceeded in one half of all years; 90% exceedance values are exceeded in 9 years out of 10. Conversely, flows are equal to or lower than the 90% exceedance values about 1 year in ten. The 7-day low flow amounts were computed as 7-day average flows reported for the last day of the period, such that the 7-day period from October 26 through November 1 is treated as a November value.

The methods used here are different from those used for the Tacoma Water HCP. The methods used for the HCP determined statistics from sorted daily values without first aggregating to average monthly and 7-day values. Methods with and without data aggregation are both commonly used, but produce different results as described below.

- The median (50% exceedance) mean monthly flows presented here are generally larger than the median monthly flows presented in the HCP[8]. Monthly flows in this report are higher because the flow volumes associated with flood events are always included in the monthly average flows. In a daily flow approach used for the HCP, the days with flood events are assigned small exceedance values (typically less than 10%) and are not reflected in the median flows. The methods used in this report to describe monthly flows were selected as being most appropriate in the context of a water balance assessment.

- The 90% exceedance 7-day low flows presented here for each month are generally smaller than the 90% exceedance flows presented for each month in the HCP. Flows reported here are lower because the methods for the HCP considered all flows in a month whereas the methods for the current work considered only the lowest 7-day period in each month. The methods used in this report to describe low flows were selected as being most appropriate in the context of discussing low flows as a limiting factor to fish utilization of the watershed.

---

[8] Monthly exceedance hydrographs for various scenarios are presented in Chapter 7 of the HCP.

Table 3.2
Green River Flow Statistics
RM 63.6 Below HHD (USGS Gage 12105900)
Basin Area = 221 square miles

Month	Mean Monthly Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	1,538	595	1,432	549
February	1,153	573	1,178	533
March	1,060	721	745	481
April	1,295	756	1,113	523
May	1,222	528	1,299	700
June	640	289	723	370
July	351	237	417	329
August	244	220	363	334
September	290	223	371	323
October	492	221	463	297
November	1,029	412	1,034	372
December	1,373	674	1,430	746

Month	7-Day Low Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	550	366	526	362
February	707	359	693	361
March	684	408	413	390
April	826	566	574	396
May	715	257	828	409
June	371	230	429	288
July	252	222	361	297
August	235	212	339	313
September	232	213	342	307
October	246	202	339	266
November	391	218	443	224
December	585	370	600	359

Table 3.3
Green River Flow Statistics
RM 60.5 Near Palmer (USGS Gage 12106700)
Basin Area = 231 square miles

Month	Mean Monthly Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	1,532	499	1,263	397
February	1,153	490	1,053	407
March	1,024	692	668	394
April	1,280	702	1,030	434
May	1,135	472	1,210	606
June	567	200	533	247
July	244	135	216	143
August	136	116	175	145
September	187	115	177	139
October	434	129	260	134
November	1,015	319	874	255
December	1,345	628	1,260	580

Month	7-Day Low Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	479	293	354	261
February	643	272	557	259
March	641	344	324	300
April	789	469	490	300
May	643	174	689	247
June	275	135	300	185
July	151	115	175	110
August	125	103	150	125
September	133	103	154	121
October	151	106	150	112
November	335	127	290	118
December	507	293	412	258

Table 3.4
Green River Flow Statistics
RM 50.0 In Gorge
Basin Area = 253 square miles

Month	Mean Monthly Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	1,632	569	1,350	430
February	1,240	536	1,147	435
March	1,101	745	746	451
April	1,339	765	1,088	491
May	1,183	499	1,260	635
June	602	220	562	274
July	272	154	241	170
August	155	133	193	165
September	208	135	205	154
October	454	143	282	149
November	1,037	352	906	271
December	1,434	664	1,344	652

Month	7-Day Low Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	539	350	394	305
February	713	321	622	309
March	718	382	430	347
April	857	516	551	354
May	678	204	741	280
June	309	159	333	211
July	173	136	198	131
August	139	122	168	142
September	148	121	171	139
October	165	122	178	130
November	362	144	311	137
December	561	339	471	312

Table 3.5
Green River Flow Statistics
RM 48.0 Below Icy Creek Springs
Basin Area = 275 square miles

Month	Mean Monthly Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	1,732	635	1,476	471
February	1,312	571	1,238	476
March	1,167	791	815	505
April	1,390	826	1,143	546
May	1,229	526	1,308	662
June	635	240	596	300
July	303	171	264	197
August	172	148	210	178
September	226	150	226	169
October	474	157	303	164
November	1,084	383	931	287
December	1,531	699	1,423	684

Month	7-Day Low Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	597	393	461	346
February	797	356	661	358
March	780	428	514	395
April	916	562	615	400
May	720	234	802	312
June	340	177	367	236
July	194	154	220	151
August	156	139	190	159
September	164	137	192	156
October	185	137	198	145
November	383	159	332	150
December	613	369	524	344

Table 3.6
Green River Flow Statistics
RM 40.7 Below Newaukum Creek
Basin Area = 310 square miles

Month	**Mean Monthly Flows, cfs**			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	1,914	747	1,685	556
February	1,466	691	1,379	622
March	1,302	866	924	592
April	1,470	884	1,233	637
May	1,306	570	1,389	706
June	689	276	658	344
July	354	200	299	224
August	204	179	237	200
September	255	175	257	193
October	508	179	338	185
November	1,162	422	976	314
December	1,695	756	1,553	733

Month	**7-Day Low Flows, cfs**			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	715	460	581	405
February	890	433	730	416
March	907	526	637	469
April	1,012	639	706	477
May	798	284	879	364
June	397	208	412	275
July	228	182	256	183
August	182	167	222	187
September	191	160	224	183
October	217	160	228	170
November	416	185	366	173
December	700	420	597	397

Table 3.7
Green River Flow Statistics
RM 31.4 Near Auburn (USGS Gage 12113000)
Basin Area = 397 square miles

Month	Mean Monthly Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	2,335	947	2,191	764
February	1,854	923	1,711	829
March	1,642	1,049	1,253	794
April	1,714	1,044	1,459	857
May	1,462	676	1,541	812
June	825	382	808	449
July	453	283	389	289
August	273	244	305	250
September	326	237	332	250
October	579	237	424	236
November	1,349	497	1,127	379
December	2,090	896	1,898	851

Month	7-Day Low Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	998	589	849	515
February	1,128	619	911	585
March	1,152	764	868	644
April	1,213	825	917	663
May	1,005	403	1,010	491
June	516	309	521	350
July	314	243	344	250
August	249	223	300	250
September	256	209	300	250
October	297	213	300	225
November	513	247	450	229
December	902	523	782	510

Table 3.8
Green River Flow Statistics
RM 23.8 Below Mill Creek (Auburn)
Basin Area = 419 square miles

Month	Mean Monthly Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	2,408	986	2,258	817
February	1,958	981	1,812	878
March	1,707	1,096	1,353	848
April	1,772	1,090	1,533	914
May	1,505	703	1,599	839
June	860	409	846	476
July	478	303	415	306
August	292	260	323	265
September	343	252	351	264
October	597	251	446	249
November	1,398	516	1,165	395
December	2,192	931	1,975	881

Month	7-Day Low Flows, cfs			
	Current Conditions		Future Conditions	
	50% Exceedance	90% Exceedance	50% Exceedance	90% Exceedance
January	1,071	619	912	543
February	1,192	658	958	623
March	1,203	825	1,007	699
April	1,291	872	973	711
May	1,064	436	1,067	524
June	547	335	552	369
July	335	258	364	265
August	266	238	318	263
September	273	224	316	260
October	317	226	317	238
November	535	261	471	243
December	959	541	833	538

3.3 Major Tributaries to Lower/Middle Green River

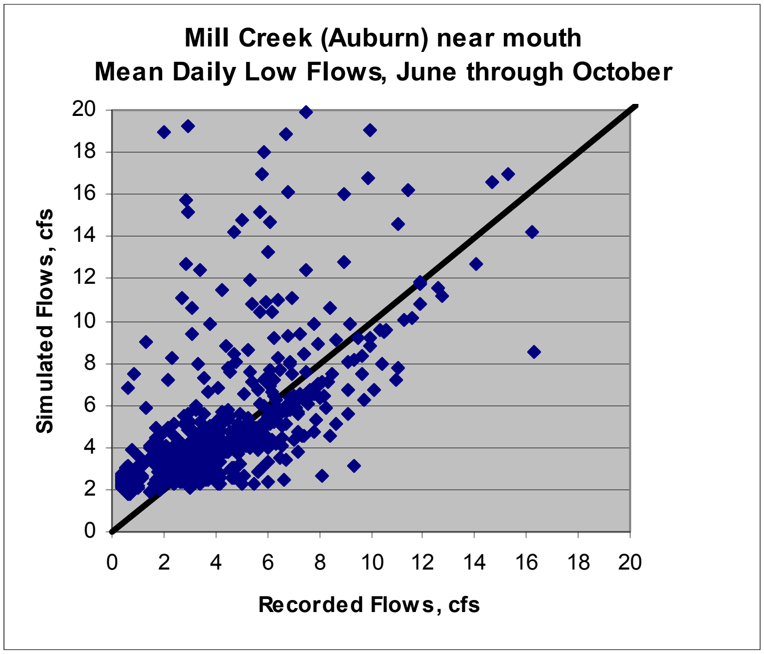
The major tributaries to the study reach of the Lower/Middle Green River are Mill Creek which joins the Green at RM 23.8, Soos Creek at RM 33.8, and Newaukum Creek at RM 40.7. These three tributaries drain a combined basin area of 106 square miles and account for 56% of the total study area downstream of the Tacoma Diversion. Flow statistics were determined for these three creeks plus Covington and Jenkins Creeks which are tributaries to Soos Creek.

The approach originally proposed to develop flow statistics for the tributary streams was to use recently-developed Hydrologic Simulation Program-Fortran (HSPF) models. This approach was proposed to make use of models which had been developed in separate studies to reflect current conditions land use and which had been calibrated to recent (post-1990) streamflow data. The HSPF model for Mill Creek (Auburn) was developed by NHC for a flood control study and, as described below, was adapted for use in the current work. HSPF models for Soos, Covington, Jenkins, and Newaukum Creek were developed by others for King County's Green-Duwamish water quality assessment (in progress).

The HSPF model of Mill Creek (Auburn) was previously developed by NHC for the City of Auburn to provide inflow hydrographs to a separate Full Equations Model (FEQ) hydraulic model of the relatively-flat lower channel. Because the focus of the previous work was on flooding in the Mill Creek valley, the HSPF model was not well calibrated to low flows, except that a constant external input of 2 cfs had been added to the middle Mill Creek basin so that the modeled flows would reasonably match recorded annual flow volumes at 29th Street NW. At the time of the previous study it was speculated that the 2 cfs flow input was associated with regional groundwater inputs originating from the White River.

In the current work, model results were compared to available flow data recorded by King County for Mill Creek at SR 181 (near the mouth of the stream), and a variable groundwater input sequence was developed to improve the model representation of low flows. Figure 3.1 below shows a scatter plot of same-day simulated versus recorded low flows for summer months for the five-year period of stream gage record, 1990 through 1995.

Figure 3.1
HSPF Model Low Flow Validation for Mill Creek (Auburn)



Our interpretation of the low flow validation results is that the model fails to adequately represent flows less than 3 cfs. King County stream gaging records were used to confirm that very low flows of less than 0.5 cfs did occur in the summers of 1994 and 1995. Table 3.9 presents the flow statistics determined from the simulation results. Because the HSPF model was unable to reproduce the very low flows observed in two of the six years of record from 1990 to 1995, the low flow statistics should be used with caution.

HSPF model calibration results for Newaukum, Jenkins, Covington, and Soos Creeks were reviewed and also found to have problems with simulation of the low flows of interest. Because these streams all have active stream gages with relatively long periods of record, it was decided that direct analysis of the recent gage records would provide the most accurate statistics to describe flows under current conditions. The USGS has operated stream gages on Soos Creek (Gage #12112600) since 1960 and on Newaukum Creek (Gage #12108500) since 1944. King County has operated stream gages on Jenkins Creek (Gage 26A) and Covington Creek (Gage 09A) since 1988.

Flow statistics for Newaukum, Jenkins, Covington, and Soos Creeks were determined by an analysis of streamflow data recorded over the 16-year period from January 1988 through May 2004, representing current conditions. Tables 3-10 through 3-13 present the results.

Table 3.9
Tributary Stream Flow Statistics
Mill Creek (Auburn) at SR 181 from HSPF Simulation Data
Basin Area = 12.3 square miles

Month	Mean Monthly Flows, cfs	
	Current Conditions	
	50% Exceedance	90% Exceedance
January	57	23
February	49	19
March	35	21
April	23	11
May	12	8
June	8	6
July	5	4*
August	5	3*
September	6	3*
October	12	7
November	37	15
December	47	25

Month	7-Day Low Flows, cfs	
	Current Conditions	
	50% Exceedance	90% Exceedance
January	16	7
February	17	7
March	14	8
April	10	6
May	6	5
June	5	4
July	4	3*
August	3	3*
September	3	2*
October	3	2
November	9	4
December	19	7

*Persistent low flows as small as 0.4 cfs were recorded during the months of July through September 1994. The HSPF simulation model was unable to reproduce those very low flows; 90% exceedance values in summer months are likely smaller than shown in the table above.

Table 3.10
Tributary Stream Flow Statistics from1988-2004 Recorded Data
Newaukum Creek Near Black Diamond, USGS Gage 12108500
Basin Area =27.1 square miles

Month	Mean Monthly Flows, cfs	
	Current Conditions	
	50% Exceedance	90% Exceedance
January	88	52
February	77	44
March	87	48
April	65	42
May	46	34
June	34	24
July	24	17
August	17	13
September	14	11
October	19	14
November	56	22
December	82	32

Month	7-Day Low Flows, cfs	
	Current Conditions	
	50% Exceedance	90% Exceedance
January	56	19
February	51	31
March	51	31
April	45	33
May	34	24
June	28	20
July	20	15
August	15	12
September	12	10
October	13	10
November	18	13
December	41	18

Table 3.11
Tributary Stream Flow Statistics from 1988-2004 Recorded Data
Jenkins Creek near Mouth, King County Gage 26A
Basin Area = 15.9 square miles

Month	**Mean Monthly Flows, cfs**	
	Current Conditions	
	50% Exceedance	90% Exceedance
January	70	34
February	60	41
March	54	41
April	49	34
May	34	25
June	25	17
July	17	12
August	12	10
September	11	9
October	13	11
November	35	16
December	51	21

Month	**7-Day Low Flows, cfs**	
	Current Conditions	
	50% Exceedance	90% Exceedance
January	44	22
February	46	29
March	42	29
April	37	28
May	29	20
June	21	15
July	14	11
August	11	8
September	10	8
October	10	8
November	14	11
December	39	17

Table 3.12
Tributary Stream Flow Statistics from 1988-2004 Recorded Data
Covington Creek near Mouth, King County Gage 09A
Basin Area = 21.5 square miles

Month	**Mean Monthly Flows, cfs**	
	Current Conditions	
	50% Exceedance	90% Exceedance
January	56	12
February	61	24
March	59	25
April	40	29
May	24	15
June	13	6
July	6	3
August	3	2
September	2	2
October	3	2
November	13	3
December	47	8

Month	**7-Day Low Flows, cfs**	
	Current Conditions	
	50% Exceedance	90% Exceedance
January	29	6
February	44	12
March	49	13
April	29	19
May	18	7
June	10	4
July	4	2
August	3	2
September	2	2
October	2	1
November	3	2
December	32	3

Table 3.13
Tributary Stream Flow Statistics from 1988-2004 Recorded Data
Soos Creek near Mouth, USGS Gage 12112600
Basin Area = 66.3 square miles

Month	**Mean Monthly Flows, cfs** Current Conditions 50% Exceedance	90% Exceedance
January	217	101
February	221	104
March	191	124
April	139	107
May	95	64
June	66	42
July	39	29
August	29	23
September	27	23
October	33	28
November	117	41
December	173	67

Month	**7-Day Low Flows, cfs** Current Conditions 50% Exceedance	90% Exceedance
January	121	61
February	156	70
March	142	78
April	105	81
May	76	46
June	54	33
July	33	26
August	27	21
September	23	20
October	25	22
November	36	30
December	108	46

3.4 Normative Flows

The normative flow discussion presented here is a summary of the early planning stages of work in progress for the mainstem Green River.

In recent years, interest has grown in evaluating the natural flow regime of river systems to gain insight into relationships between flow conditions, physical processes and ecological response. Recent ecological research, including guidance from the National Research Council, NOAA Fisheries and others, has indicated that all aspects of the flow regime have relevance for habitat protection[9,10].This view is summarized in the following statement from a report by Spence et al.[11]: "Protection of salmonid habitats requires stream flows to fluctuate within the natural range of flows for the given location and season." This is in contrast to legal requirements in the State of Washington that rely on establishment of minimum instream flows as the primary flow-related requirement for fish habitat protection.

[9] NRC (National Research Council). 1992. Restoration of aquatic ecosystems: science, technology, and public technology. National Academy Press, Washington, D.C.

[10] Poff, L. N., J. D. Allan, M. B. Bain, J.R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks and J.C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47(11) 769-784.

[11] Spence, B.C., G.A Lomnicky, RM. Hughes, R.P. Novitzki. 1996. An ecosystem approach to salmonid conservation. TR-4501-96-6057. ManTech Environmental Research Services Corp., Corvallis, OR.

Research suggests that salmonids evolved with life histories reliant on the entire range of flow variation in a naturally flowing river: the magnitude, frequency, timing, duration, and rates of change of various flow events, annual maxima and minima. The research further suggests that all of these aspects of the flow regime should be evaluated in examining hydrologic factors for salmon production in the Pacific Northwest. Changes in hydrologic parameters become more or less important depending on ecological and geomorphic factors such as gravel regime, wood loading and recruitment, and channel complexity within the river, the life histories of the species of interest, the degree to which various reaches have been altered by channelization and construction of levees and revetments.

As a result of these issues, King County initiated the Normative Flow Studies project to develop a method for evaluating the effects of anthropogenic alteration of flow regimes on aquatic ecosystems, including effects of altered flows on the persistence and recovery of salmonids. The method will be applied in two ways: (1) to assess the effects (and implications for conservation) of existing departures in flow patterns (from a pre-altered condition) in King County streams and rivers, and (2) to evaluate the effects of flow alterations on physical and biological systems. King County selected the Green River as a case study for developing this approach further for larger river systems.

The Middle Green River Flow Investigation was initiated in 2004 as a collaborative effort to identify flow-related research priorities for the middle reach of the Green River and to develop a program to implement studies to address the priorities. The effort includes staff from King County, US Army Corps of Engineers, USGS, American Rivers, Washington Departments of Fish and Wildlife, and Ecology. Current and upcoming work is focused on enhancing our understanding of the relationship between river flow patterns, physical responses, and biological parameters. Three draft "themes" have been developed for consideration as part of the investigation.

- Theme 1: A retrospective study of the Green River comparing channel conditions prior to and after construction of Howard Hanson Dam.
- Theme 2: Macrohabitat analysis and high flow connectivity that includes describing, mapping and summarizing off-channel habitat conditions for high flows.
- Theme 3: The influence of physical processes on aquatic and riparian habitat.

All three of these studies have potential to contribute substantial information to flow-habitat relationships in the Middle Green River that will aid in salmon conservation and recovery.

Theme 1 is the first priority and more detailed scoping has been initiated. The key hypothesis is that closure and operation of Howard Hanson Dam and the modifications in channel structure (e.g., construction of levees and revetments, channel straightening and dredging) for flood control purposes have altered the rates, magnitudes and spatial arrangement of ecosystem processes and functions compared to the pre-dam state. The information learned from addressing this hypothesis will be used to address a follow-up hypothesis: the flow regime during the post-dam period causes geomorphic and habitat variability (in functional, structural and process attributes) sufficient to sustain a viable salmonid population.

The study encompasses the river and its valley from the upper limits of the Green River at approximately river mile 88, downstream to the historic confluence with the now-diverted White River at approximately river mile 31. The time frame covered by this study varies, but generally covers the period from approximately 1856 to the present day. Certain attributes will be examined for a more limited study period from 1936 to present (e.g., hydrologic/gauging data, photographic record), while other attributes may go back to 1856 (e.g., written accounts, anecdotal information).

Theme 2 Hypothesis: Scheduled releases of high flow and selected habitat improvement projects will increase the area and complexity of off-channel habitat for fish in the Middle Reach of the Green River. An increase in habitat area will depend on river stage, secondary channel density, and width of channel migration zone. An increase in usable habitat area will depend on timing of releases and concurrent life stage of fish species.

Study Design and Objectives: Flood storage behind Howard Hanson Dam has reduced high flows downstream. Flows in the Middle Reach of the Green River have not exceeded 12,000 cfs since 1962. Pre-regulation high flows ranged from 12,000 cfs (.50 probability), to 21,000 cfs (.10 probability), to 34,000 cfs (.01 probability)[12]. Flood storage has altered the hydrologic regime of the river and reduced the extent of overbank flows (connectivity) in floodplain and other off-channel areas.

The overall study design is to describe, map, and summarize off-channel habitat conditions at specified high flows on the Middle Reach of the Green River in King County, WA. Habitat assessment areas will include the floodplain at specified flows, historic channel locations, channel migration hazard areas, secondary channels, and associated landforms outside the main channel of the river. Objectives of the study are to define and quantify potential fish habitat benefits of more frequent periods of flows up to 12,000 cfs at Auburn to produce overflows in off-channel areas on the river.

Theme 3 involves the investigation of physical processes on aquatic habitat at the scale of channel forms (e.g., pools, riffles, runs). The results will be used to develop an understanding of how habitat conditions for these general types of channel forms will respond to human manipulations of streamflow, sediment load, channel morphology, and riparian vegetation.

Hypothesis: High flows can be managed to allow ecological functions (e.g., creating and maintaining off-channel habitat, recruitment of large woody debris, patch turnover) without negative consequences including redd scour, depletion of limited sediment supply below Howard Hansen dam, and reducing large woody debris and instream habitat structure. There are a number of important secondary hypotheses related to specific habitat responses. For example, the probability of chinook salmon redd scour increases with streamflow but can be reduced by limiting the frequency and duration of flows exceeding some threshold and managing flows when salmon are selecting spawning sites.

Study Design and Objectives: This study will examine the interactions between streamflow, sediment, and large woody debris (LWD) in the middle Green River. It will require information about channel form and hydraulic conditions at representative sites within the Middle Green River. Hydraulic and sedimentological conditions would be analyzed at the sites to characterize sediment transport regime (e.g., threshold of motion, partial transport, equal mobility of all particles). The sediment transport investigation would include experiments using tracer cobbles in Chinook salmon redd/non-redd locations to assess scour during winter. The investigation of LWD would include a retrospective assessment of in-channel LWD identified from historical aerial photos, US Army Corps of Engineers data on new wood placement, and multispectral aerial imaging. Remote inventorying would be verified and supplemented by field surveys of the location (relative elevation and location in channel) of selected pieces of LWD. The LWD investigation would quantify LWD retention time in selected reaches; quantify streamflow levels for distinct types of interactions (e.g., streamflow that transport key pieces for log jams, transport smaller debris, transport sediment around LWD; or provides cover or pools adjacent to LWD).

[12] King County. 1993. Green River channel migration study. King County Dept. Public Works, Surface Water Management Division. Seattle WA. 45 p.

4 Fisheries-Perspective Assessment of Existing Streamflows

4.1 Salmon Utilization

The following section summarizes information on salmonid species in the Green River study area, including Chinook, chum, coho, pink and sockeye salmon, and steelhead trout. Figure 4.1 shows the distribution of Chinook salmon in the study area. Figure 4.2 shows the distribution of chum, coho, pink and sockeye salmon.

Chinook Salmon

Adult and juvenile Chinook salmon (*Oncorhynchus tshawytsha*) are present within the lower end of the study area to River Mile (RM) 61. Anadromous salmon have been prevented from accessing the upper Green River above RM 61 since 1911 when a diversion dam was constructed by the City of Tacoma for its domestic water supply. Howard Hanson Dam was subsequently built 3.5 miles upstream of the diversion dam (RM 64.5) by the Army Corps of Engineers to provide flood protection and water storage for low-flow augmentation in 1963. Juvenile Chinook salmon are planted above Howard Hanson Dam by the Muckleshoot Indian Tribe to rear in the Upper Green River sub-watershed.

The primary spawning areas for summer/fall Chinook salmon in the study area are the mainstem Green River and major tributaries including Big Soos Creek and Newaukum Creek. Spawning along the mainstem river begins at approximately RM 25, about 1.2 miles upstream from the confluence with Mill Creek (Auburn). The highest concentration of observed spawners is between RM 33.8 and 50.3, based upon analysis of WDFW data by Malcom[13]. Summer/fall Chinook adults have been observed entering the Duwamish River in mid-June and continuing into October. The downstream end of this reach (RM 33.8) corresponds approximately to the confluence with Soos Creek. Spawning in the mainstem Green River occurs from early September to early November[14,15].

[13] Malcom, R. 2002. Annual variation (1997-2000) in the distribution of spawning Chinook in the mainstem Green River (WRIA 09.001), King County, Washington, Draft Report. Ecocline Fisheries Habitat Consulting LTD. Burnaby, BC Canada.

[14] Williams, R., R. Laramie, and J. Ames. 1975. A catalog of Washington streams and salmon utilization, Vol 1, Puget Sound Region. Washington Department of Fisheries, Olympia, Washington.

[15] WDFW Spawning Ground Survey Database

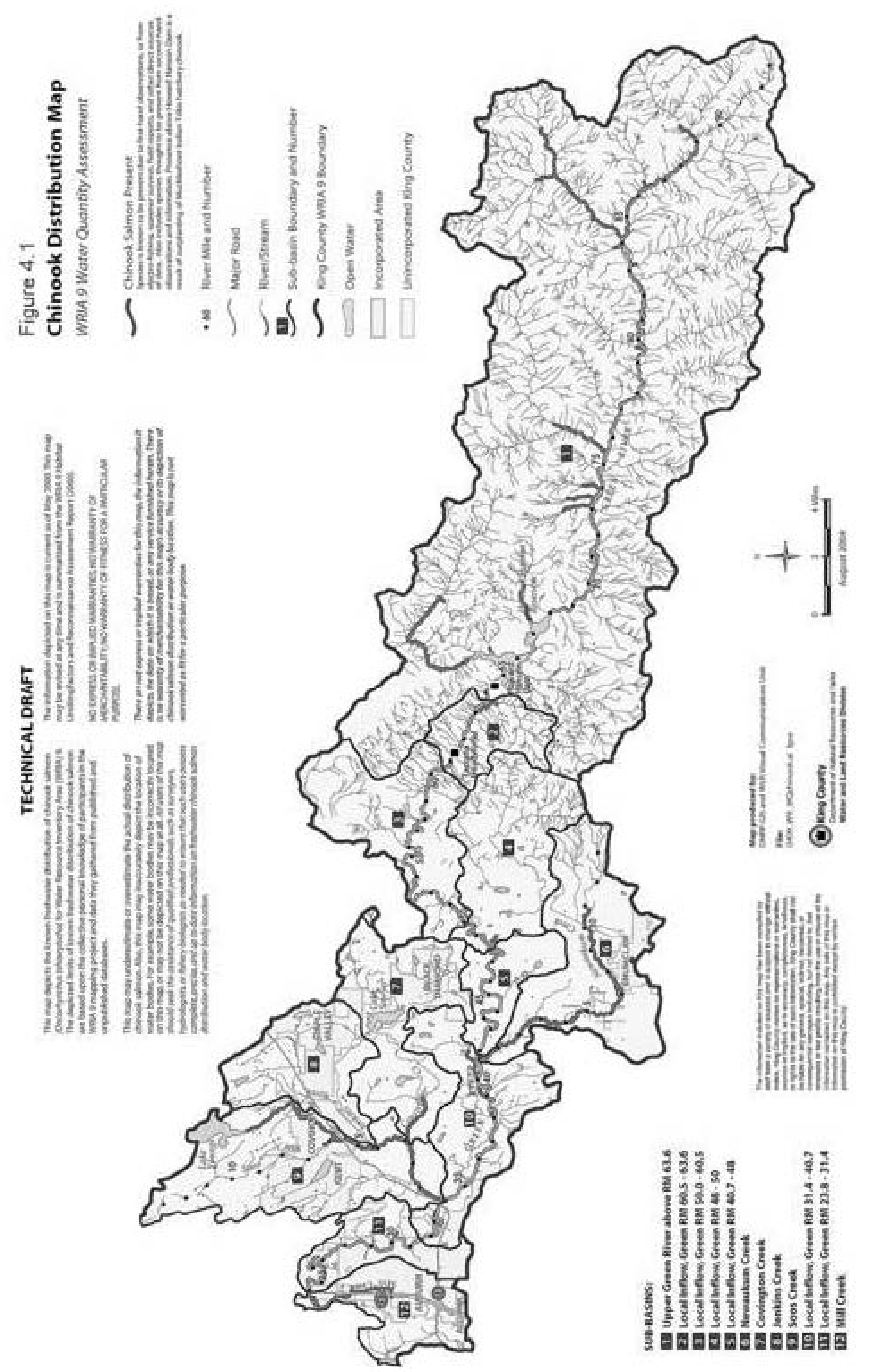


Figure 4.1. Chinook Distribution Map (Placeholder for 11 x 17 color sheet)

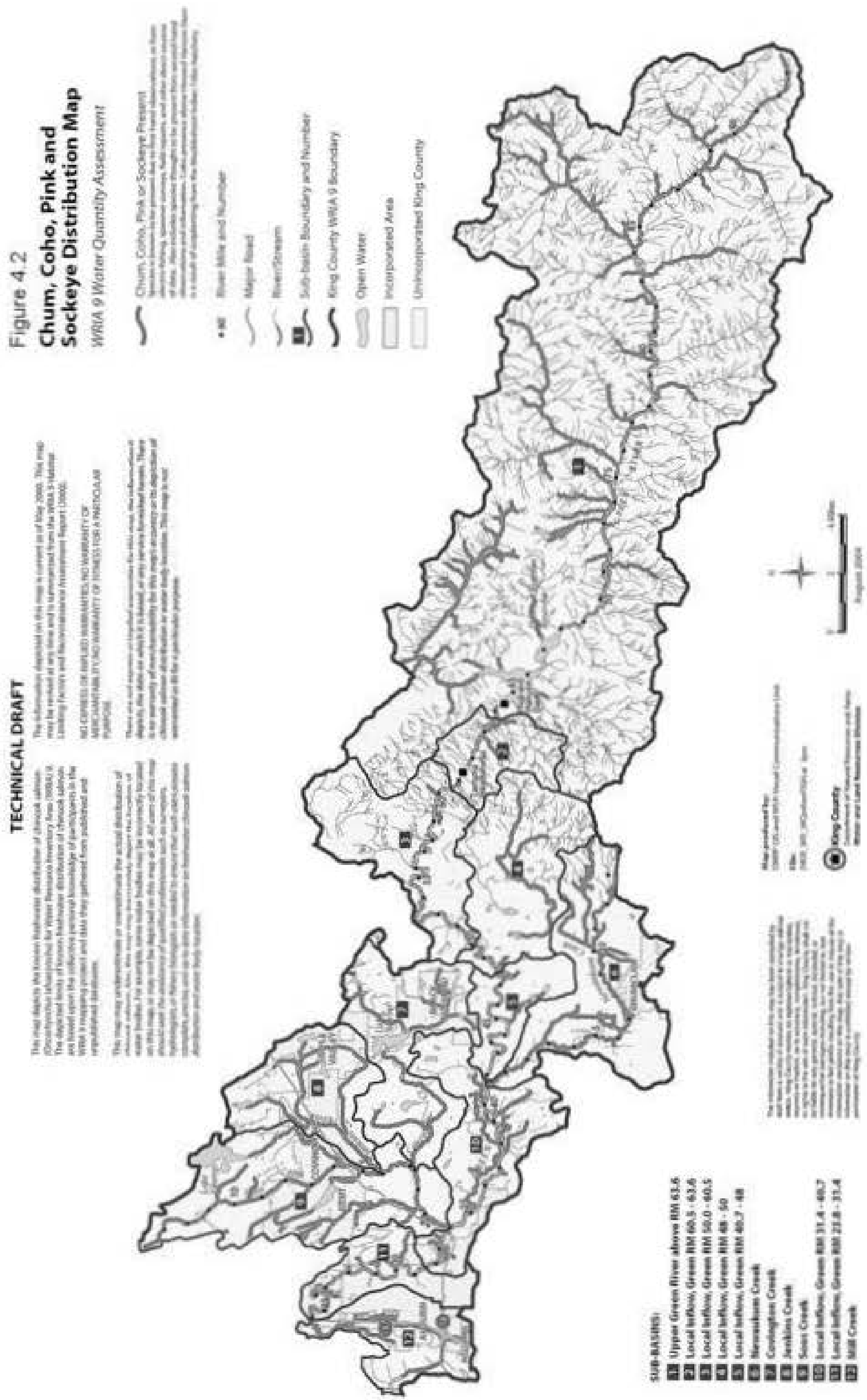


Figure 4.2. Chum, Coho, Pink, and Sockeye Distribution Map (Placeholder for 11 x 17 color sheet)

Juvenile Chinook salmon rearing habitat in the Middle Green is located primarily between RM 33.8 and 60.8[16]. Juvenile Chinook salmon produced in the study area are thought to have at least five life history types. The most common life history types, based upon a recent conceptual model[17] are believed to be:

- *Estuary-Reared Fry*: Fry spend a short time in the study area (several days to several weeks) following emergence, and then migrate quickly downstream to rear in the Duwamish Estuary for two to three months.
- *Marine Direct Fingerlings*: Fingerlings rear near the spawning grounds within the study area for one or two months before migrating relatively quickly through the estuary to Puget Sound.

Historically, both a spring run and summer/fall run of Chinook salmon were believed to be present[18]. Currently, spring Chinook are believed to be locally extirpated in the Green River, although spring Chinook have occasionally been observed in the mainstem river[19]. Spring Chinook are believed to have begun entering the Duwamish River in May and June and remain in the river until spawning in August and September[20]. The Green/Duwamish and Newaukum Creek summer/fall Chinook stock status were rated as healthy in the 1992 Washington State Salmon and Steelhead Inventory[21]. Chinook salmon in western Washington, including those in the Green River, were listed as a threatened species under the provisions of the Endangered Species Act (ESA) in 1999.

Two hatcheries located on tributaries to the Green River currently produce fingerling and yearling size juveniles that are released in May through mid-June. Soos Creek Hatchery, operated by Washington Department of Fish and Wildlife, releases subyearling Chinook in Soos Creek and yearling Chinook in Icy Creek. The Keta Creek Hatchery, located on Crisp Creek, is operated by the Muckleshoot Indian Tribe and produces only fingerlings.

Coho Salmon

Coho salmon (*Oncorhynchus kisutch*) are widely distributed throughout the study area including the mainstem Green River, Newaukum Creek, Soos Creek, Mill Creek, and Springbrook Creek. Adult coho salmon are prevented from migrating above the Tacoma Diversion Dam at RM 61, but juvenile coho

---

[16] R2 Resource Consultants, Inc. 2002. Juvenile Salmonid Use of Lateral Stream Habitats Middle Green River, Washington. 2000 Data Report. Prepared for U.S. Army Corps of Engineers, Seattle District. Redmond , WA.

[17] Ruggerone, G. and D. Weitkamp. 2004 WRIA 9 Chinook Salmon Research Framework: Identifying Key Research Questions about Chinook Salmon Life Histories and Habitat Use in the Middle and Lower Green River, Duwamish Waterway, and Marine Nearshore Areas. Prepared for WRIA 9 Steering committee. Prepared by Natural Resource Consultants, Inc., Parmetrix, Inc., and the WRIA 9 Technical Committee. Seattle, WA.

[18] Nehlsen, W., J. Williams, and J. Lichatowich. 1991. Pacific Salmon at the Crossroads: Stocks at Risk from California, Oregon, Idaho, and Washington. Fisheries, Volume 16, No.2

[19] King County Water and Land Resources and WRIA 9. 2004. WRIA 9 Strategic Assessment Report- Scientific Foundation for Salmonid Habitat Conservation. Draft. Prepared for WRIA 9 Steering Committee. Seattle, WA.

[20] Kerwin, J. and T.S. Nelson (Eds.). 2000. Habitat limiting factors and reconnaissance assessment report, Green/Duwamish and Central Puget Sound watersheds (WRIA 9 and Vashon Island). Washington Conservation Commission and King County Department of Natural Resources, Seattle, WA.

[21] Washington Department of Fish and Wildlife (WDFS) and Western Washington Treaty Indian Tribes (WWTIT). 1994. 1992 Washington State salmon and steelhead stock inventory, Appendix 1 Puget Sound stocks. WDFW, Olympia, WA.

salmon are released above Howard Hanson dam by the Muckleshoot Indian Tribe (with approximately 500,000 released in 2004).

The Green River coho population consists of the Green River/Soos and Newaukum Creek stocks[22], which vary greatly in timing. The Green River/Soos stock begins entering the Duwamish between September and early December, with spawning between November and early February[23]. The Newaukum Creek stock migrates later, with spawning into mid-January[24]. Juvenile coho salmon fry emerge in April and May and remain in freshwater for rearing for a year following emergence.

The Green River/Soos Creek stock is listed as healthy in the 1992 Washington State Salmon and Steelhead Inventory[25]. The Newaukum Creek coho stock is rated as depressed in the inventory. Hatchery releases consist of coho yearlings by Washington Department of Fish and Wildlife at the Soos Creek hatchery and coho yearlings by the Muckleshoot Indian Tribe at Crisp Creek.

Chum Salmon

Chum salmon (*Oncorhynchus keta*) are present in the mainstem Green River to RM 60.6, in Newaukum Creek, Crisp Creek, Burns Creek, and Tributary 09.0098[26]. The population consists of two stocks, the Green River fall-run chum and Crisp Creek fall-run chum salmon. The Green River fall-run chum stock is rated as unknown and the Crisp Creek fall chum is considered healthy[27]. The Muckleshoot Indian Tribe releases hatchery raised chum subyearling at Crisp Creek.

Pink Salmon

Pink salmon (*Oncorhynchus gorbusha*) are present in odd years in the study area below the Green River at RM 42 and in Newaukum Creek. The stock status is rated as unknown but presumed depressed[28]. Until recently, pink salmon were believed to be extirpated from the system. However, small numbers of adult pink salmon were observed spawning in the mainstem beginning in the 1990's and juveniles have been captured during sampling[29]. Pink salmon were observed entering the mainstem Green River in

---

[22] Ibid.

[23] King County Water and Land Resources and WRIA 9. 2004. WRIA 9 Strategic Assessment Report- Scientific Foundation for Salmonid Habitat Conservation. Draft. Prepared for WRIA 9 Steering Committee. Seattle, WA.

[24] Washington Department of Fish and Wildlife (WDFS) and Western Washington Treaty Indian Tribes (WWTIT). 1994. 1992 Washington State salmon and steelhead stock inventory, Appendix 1 Puget Sound stocks. WDFW, Olympia, WA.

[25] Ibid.

[26] King County Water and Land Resources and WRIA 9. 2004. WRIA 9 Strategic Assessment Report- Scientific Foundation for Salmonid Habitat Conservation. Draft. Prepared for WRIA 9 Steering Committee. Seattle, WA.

[27] Washington Department of Fish and Wildlife (WDFS) and Western Washington Treaty Indian Tribes (WWTIT). 1994. 1992 Washington State salmon and steelhead stock inventory, Appendix 1 Puget Sound stocks. WDFW, Olympia, WA.

[28] Ibid.

[29] King County Water and Land Resources and WRIA 9. 2004. WRIA 9 Strategic Assessment Report- Scientific Foundation for Salmonid Habitat Conservation. Draft. Prepared for WRIA 9 Steering Committee. Seattle, WA.

August with spawning in September and October. Unusually high numbers (300,000) of adult pinks were estimated by WDFW in 2004 on the spawning grounds. The fry are believed to emerge in March and April and rapidly migrate to the estuary.

Sockeye Salmon

A small number of sockeye salmon (*Oncorhynchus nerka*) have been observed in the mainstem Green River within the study area. The Green River sockeye population is documented in the Status Review of Sockeye Salmon in Washington and Oregon[30]. This species is typically associated with lakes but other river-run populations are documented in the Pacific Northwest. Stock status is not rated in the 1992 Washington State Salmon and Steelhead Inventory (SASSI)[31].

Steelhead Trout

There are two winter steelhead (*Oncorhynchus mykiss*) stocks characterized in SASSI in the Green-Duwamish River basin: the native wild spawning population and the early timing hatchery stock. Population trends of Green River wild winter steelhead in the early 1990s began a steady decrease similar to those of many other regional stream systems. From 1978 to 1998, escapement estimates ranged from approximately 960 to 2800 fish. The current hatchery summer steelhead stock in the Green River Basin is a non-native (hatchery introduced) stock with origins from the Washougal and Skykomish Rivers. Hatchery summer steelhead have been released in the Green River since 1965. River entry occurs from April through October with spawning from mid–January through mid-March. They are found in Newaukum Creek, Soos Creek and its larger tributaries, Mill Creek and Springbrook Creek.[32]

4.2 Salmonids and Water Quantity on the Mainstem Green River

The Howard Hanson Dam is operated to accomplish two purposes for the Green River: (1) flood control and (2) low flow augmentation through management of a summer conservation pool that currently is approximately 30,000 acre-feet. Low flow augmentation is managed jointly through real-time flow management in coordination with the Army Corps of Engineers (ACOE). The intent is to meet resource and fisheries needs below Howard Hanson Dam. Coordination is done with the co-managers (Muckleshoot Indian Tribe (MIT) and WDFW) along with other federal, state and local resource agencies and non-governmental organizations including Tacoma Public Utilities (TPU), Washington Department of Ecology, U.S. Fish and Wildlife Service, King County and Friends of the Green River. These water management coordination meetings occur about twice a month from spring through fall to address a range of water resource management needs, including balancing the habitat needs of salmonids while accommodating a variety of other competing uses. The following discussion is taken in part from the perspective of resource managers trying to meet water needs for fish in the Green River[33] with a focus on the mainstem.

---

[30] NOAA Technical Memorandum NMFS-NWFSC-33 Status Review of Sockeye Salmon from Washington and Oregon, December 1997.

[31] Washington Department of Fish and Wildlife (WDFS) and Western Washington Treaty Indian Tribes (WWTIT). 1994. 1992 Washington State salmon and steelhead stock inventory, Appendix 1 Puget Sound stocks. WDFW, Olympia, WA.

[32] Kerwin, J. and T.S. Nelson (Eds.). 2000. Habitat limiting factors and reconnaissance assessment report, Green/Duwamish and Central Puget Sound watersheds (WRIA 9 and Vashon Island). Washington Conservation Commission and King County Department of Natural Resources, Seattle, WA

[33] Engman, G. personal communication, 2005. and
Coccoli, H., Muckleshoot Indian Tribe Fisheries Division comment letter dated May 2005.

There is rarely enough water to meet all resource needs. Available storage (the 30,000 acre-feet conservation pool) as well as project mandates and rule curve constraints dating from the original project authorization for HHD combine to create resource protection conflicts. Major instream flow needs during the conservation pool allocation period (early summer through fall) include: (1) protection of wild winter steelhead redds through fry emergence, (2) adequate summer low flows for juvenile steelhead and salmon rearing, and (3) sufficient flows for Chinook spawning. In the majority of years, none of these needs can be fully met. Providing enough water for even one of these needs means compromising the others. The annual process of allocating available reservoir storage to instream flows is more a process of distributing impacts in order to achieve the best overall balance for resource protection.

Because all needs cannot be met, priority is given to flows for steelhead incubation and Chinook spawning. Dividing available storage between these two needs, along with other factors that have driven project operations in individual years, means that up to 50 percent of steelhead redds may be dried up before fry have a chance to emerge. If summer-fall precipitation is below normal, Chinook have access to a fraction of available spawning habitat and are forced to spawn in locations vulnerable to streambed scour. Stream flow from about mid-July through most of September is usually not augmented beyond project mandates (110 cfs below the Tacoma Headworks) and relies heavily on local inflows and rainfall. However, both the Tacoma Habitat Conservation Plan and the 1995 Agreement between MIT and the City of Tacoma have provisions to not allow Green River flows to drop below specific thresholds as measured at the USGS gauge at Auburn (see Chapter 2 for more detail). In the past, Tacoma has also helped ensure greater quantities of water were available in the fall to benefit Chinook salmon.

Summer rearing habitat quantity and quality, due to low flow and high water temperatures, are an increasingly significant issue. Protection and, wherever possible, restoration of inflows to the mainstem Green River is essential. A logical solution would appear to be increased storage. The Howard Hanson Dam Additional Water Storage Project Phase 1 (AWSP), authorizing an additional 20,000 acre-feet of storage, will be implemented as early as 2006. That increment, however, is dedicated to municipal supply. Cooperative management for increased resource protection may be possible initially, but as municipal and industrial demand increases this does not appear likely to be a long term solution. Additionally, there may be serious issues in terms of "starving" the Green River below the dam while trying to capture a total of 50,000 acre-feet of storage on an annual basis. Recent occurrences of below normal precipitation and snow pack have made capturing 30,000 acre-feet, in the existing project, challenging. Long term climatic predictions for more of the same will exacerbate these issues. A Phase 2 Project would add another 10,000 acre-feet of storage (60,000 acre-feet total) that would be dedicated to flow augmentation. Benefits of going forward with this further expansion would have to be weighed against even more impacts to storing this volume of water.

While streamflow augmentation is a critical need in the Green River to meet instream flows, it is important to note that reservoir refill operations are also challenging. Reservoir refill begins in late February or early March and extends through May. The late winter-spring refill period is important for salmon life stages in the Green River. The connectivity and availability of side channels and other shallow, low velocity lateral habitats downstream of HHD are significantly reduced during refill. Side channel and lateral habitats are especially important for spawning, incubation, emergence, and early rearing for Chinook, chum, and coho salmon during winter and spring. Chinook fry, after their emergence prior to and during refill, tend to use slow water areas along stream margins and a variety of other edge habitats such as gravel bar pools near vegetative or woody cover. In addition, higher flows that promote less predation and higher survival rates of out-migrating chum and Chinook juveniles are also reduced during spring refill as water is put into storage.

Cooperative efforts, through the water management coordination noted above, help to minimize the effects of storage on downstream habitats and salmon life stages. This has included earlier refill to minimize the proportion of inflow captured in the reservoir (capture rate), and the use of a proportional capture rate as inflows vary. Additional efforts need to be developed in cooperation with the ACOE, TPU, MIT and WDFW to minimize downstream impacts on fish during refill operations. While more reservoir storage may seem like a logical solution to water shortages for fish, it is increasingly apparent that increments in new storage in the reservoir require more aggressive refill rates which may cause further impacts on habitat and life-stage survival. This can be exacerbated in years with low snow pack or dry winter-spring conditions, when it will be challenging to promote the hydraulic connection of side channels and meet other downstream resource needs while achieving additional water storage up to 50,000 acre-feet.

Instream flow regulations and agreements providing for minimum instream flows are an invaluable element of resource protection. The 1995 agreement between MIT and the City of Tacoma provides for development and implementation of a steelhead redd monitoring program (see Section 2.7 – Real-time Monitoring of Steelhead Spawning and Incubation) so that the location of steelhead redds can be included in flow management decision making by the Water Management Coordination Committee. Peak steelhead spawn timing typically occurs in late April to early May and fry emergence typically occurs in late June through early July. Full protection of all steelhead redds is usually not possible, in part due to the need to retain stored water to augment flows during Chinook spawning in the late summer and early fall when inflows to the river are low. Steelhead redd monitoring has provided important information to improve management of summer flows, but it is important to still recognize the limitations of static minimum flows, particularly when flows are higher during steelhead spawning. Providing full-term wild steelhead redd protection through fry emergence is a common example where static minimum flows can fall short. Flows necessary to provide that protection vary greatly from year to year depending on actual flows when spawning takes place. The greater the flow during spawning, the greater the flow must be through emergence. This is an especially acute problem on the Green River where flows during steelhead spawning often vary widely while flows in July, the time of peak emergence, vary little from base levels.

It is important to note that the Green River instream flow requirements or agreements that condition the City of Tacoma Second Diversion Water Right (SDWR) only apply when water is being directly diverted or when water is being placed into storage. They do not apply when previously stored water is being diverted. This means SDWR instream flow provisons do not apply during the critical summer low flow period when SDWR water is being retrieved from Howard Hanson reservoir. However, before withdrawing water under the SDWR, Tacoma Water must adhere to the following seasonal minimum flows at the Palmer and Auburn USGS gauges: July 15 to September 15 – 200 cfs at Palmer and 400 cfs at Auburn; September 16 to July 14 – 300 cfs at Palmer. When these instream flow conditions are met, water can be diverted either directly to the water supply system, or to storage in the reservoir to be used at a later time. At other times, Tacoma will contribute water to the river to ensure that flows do not fall below agreed upon levels at the Auburn USGS gauge committed to by Tacoma as part of the Second Supply project.

Finally, lower flows in the Green River tributaries (Newaukum, Soos, Covington, Jenkins and Mill creeks), particularly during summer months, have had an impact on salmonids. Green River tributaries historically supported more abundant and diverse salmonid populations. WDFW surveys indicate declining numbers of spawners in these tributaries in recent years, especially for steelhead. Declining summer rearing flows and elevated peak flows due to water withdrawals and land development are thought to impact salmonids in these tributaries (see Chapter 9 for more detail on reduction in summer flows).

5 Significant Groundwater Inputs to the Green River

Prior work has identified two reaches along the Green River with significant, concentrated groundwater inputs from external or closed-depression sub-basins. The first is in the vicinity of Auburn, where substantial amounts of groundwater from the adjoining White River basin (WRIA 10) flows to aquifers connected to the Green River. The City of Auburn assessed conditions in the reach from RM 25.5 to RM 35 as part of its 1999 hydrogeologic characterization effort[34]. The second reach extends from RM 48 to 52, where several large springs flow into the Green River. The largest springs are believed to be the discharge points from the adjacent Coal Creek and Deep Creek closed depression basins, which are included in this study as part of Green River Local Inflow Sub-basin 7.

In the two reaches with significant groundwater inputs, Green River flows are expected to increase in the vicinity of the groundwater contributions. In reaches with less pronounced groundwater inputs, the river may gain water from, or lose water to, the underlying groundwater system. These gains and losses may occur within relatively localized areas or along longer reaches of the river, as a discrete event or a long-term condition. Two main factors drive the river-groundwater dynamic: the relationship between water levels in the river and in the underlying (or adjacent) materials, and the permeability of the river bed and bank materials, including bedrock, incised by the river. If river levels are higher than groundwater levels at a given location and the materials are reasonably permeable, water flows from the river into the aquifer[35], a condition known as "losing." On the other hand, if river levels are lower than groundwater levels and the materials are reasonably permeable, water flows into the river from the aquifer—the "gaining" condition.

River-groundwater interactions along the Green River play a crucial role in supporting habitat components for fish and other aquatic species. The dynamic exchange of surface water and groundwater creates unique physical, chemical, and biological conditions. For example, the discharge of cold groundwater into the river can maintain the low water temperatures that fish require, even during the warm summer months. It also maintains habitat features such as wall-based channels and floodplain wetlands that might otherwise dry up in the summer months. Groundwater discharge is influenced not only by conditions along the river but also by the upgradient flow paths that contribute to these conditions. Because of their potential impacts on aquatic habitat, groundwater inputs need to be considered by land use and water resource decision-makers.

The two reaches of significant groundwater inputs to the Green River which are discussed here are not the only sources of groundwater to the river. However, the vast majority of springs and seeps which are the interface from groundwater to surface water are distributed throughout the basin and take on the temperature and water quality characteristics of surface flows before reaching the mainstem Green River. For example, groundwater aquifers are the source of summer base flows in the basin's tributary streams—including Jenkins, Covington, Soos, Newaukum, and Mill Creeks—but those same base flows are regarded as surface water inputs to the Green River. There are numerous groundwater seeps and springs which discharge directly to the Green River along its length, but are typically small and ignored. The areas of groundwater inputs discussed below are of particular interest because of very large and localized flow volumes which are both beneficial to river habitat conditions and attractive as potential sources of water supply.

---

[34] Pacific Groundwater Group, 1999. *1999 Hydrogeologic Characterization, City of Aubur*n. Consultants' report prepared for the City of Auburn.

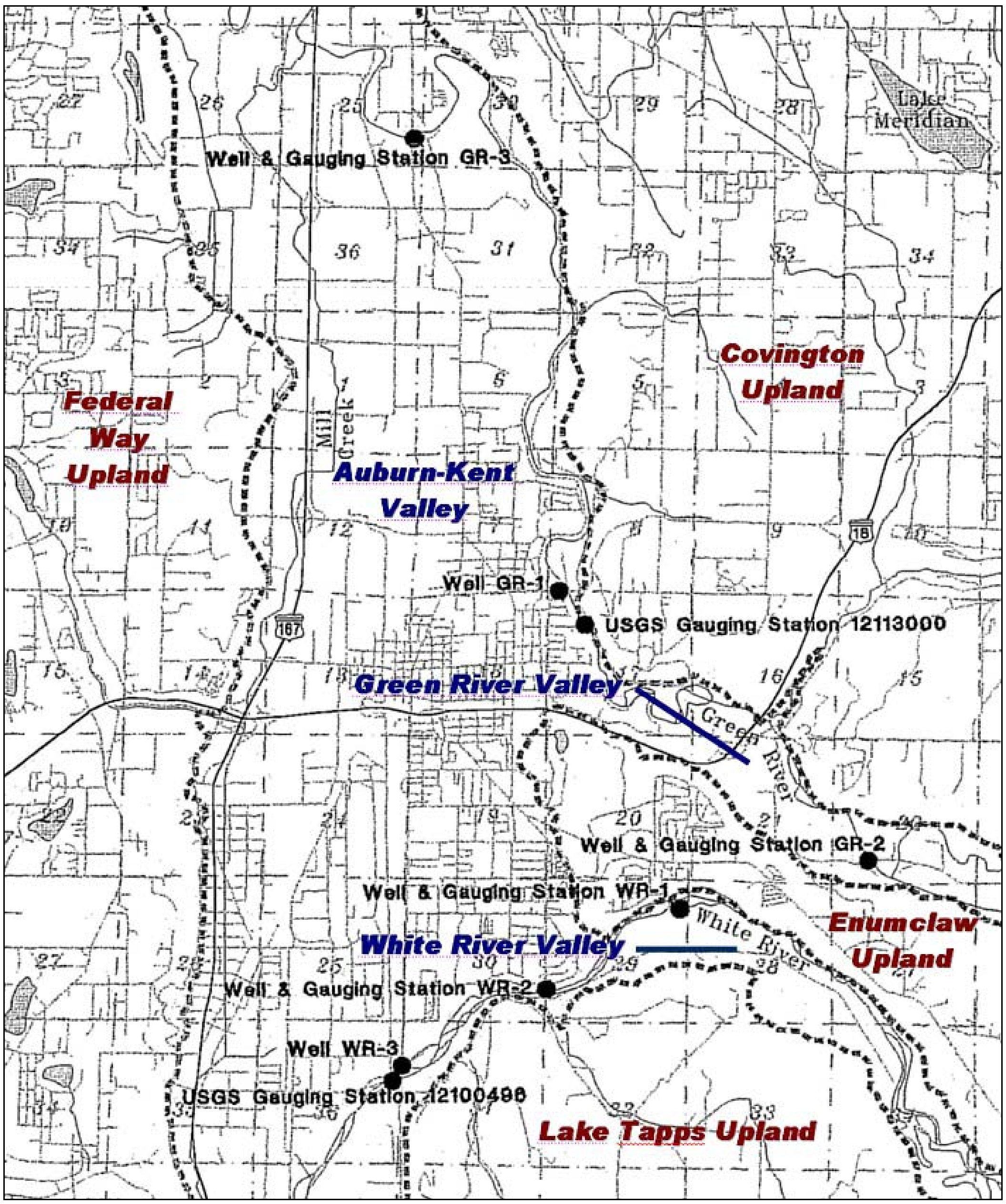
[35] An aquifer is a saturated permeable geologic unit that is capable of transmitting significant quantities of water under ordinary hydraulic gradients. "Significant quantities" is in the context of providing useful amounts of water to springs or wells.

5.1 Groundwater Flows from the White River, WRIA 10

5.1.1 Groundwater Discharge at the Green River near Auburn

In the mid to late 1990s, the City of Auburn installed a network of surface water and groundwater monitoring stations in the Green River vicinity. These stations included wells and nearby stream gauges instrumented with measuring and data logging equipment. Figure 5.1 shows the locations of these monitoring stations. Two stations (GR-1 and GR-3) are located along the Green River in the Auburn Kent-Valley and one (GR-2) is located in the Green River Valley.

Figure 5.1
Geologic Features and Locations of Monitoring Stations



Several factors were characterized to assess the hydraulic connection between the groundwater system and the Green River in these areas: geologic relationships, differences in river and groundwater levels, and river flows.

5.1.1.1 Geologic Relationships

Near its confluence with the Auburn-Kent Valley (at approximately RM 32), the Green River is underlain by an aquifer system composed of two hydrogeologic units—the alluvial deposits (Qal) and the glacial Vashon recessional deposits (Qvrd). Farther upgradient, in the Green River Valley, the aquifer system consists predominantly of Qal. Wells GR-1, GR-2, and GR-3, which lie adjacent to the Green River, locally penetrate silt and fine sand within much of the upper part of the Qal. These relatively fine-grained layers lie at or above river level, likely controlling groundwater flow to the river. These layers have a lower hydraulic conductivity than the surrounding coarser sediments; consequently, groundwater flow through these fine-grained layers has a significant vertical component.

5.1.1.2 River & Groundwater Levels

Groundwater flows down the Qal aquifer beneath the Green River Valley and then enters the Qal/Qvrd in the Auburn-Kent Valley. It then flows northward through the Qal/Qvrd aquifer, roughly following the Green River (Figure 5.1). The river gains flow in some reaches and loses flow in others, as discussed below.

- **RM 35—Well & Gauging Station GR-2**. At this station, which lies 4 miles upstream of the USGS stream gauge #12113000, the river loses flow to the groundwater system. Water levels in the Qal at Well GR-2 are always lower than river stage at SG-GR-2, by about 0.5 to 1 foot.

- **RM 31—Well GR-1 & Stream Gage USGS #12113000, Green River near Auburn.** At this location, the Green River gains flow from the aquifer, as indicated by the relationships between groundwater levels and river stage[36]. The water level difference at the gauge and well is generally small—only 1 foot most of the year. Because gradients are upward, groundwater augments river flows at all times except possibly during extreme, short-term flood peaks. This pattern is consistent with water level contours for the Qal aquifer, which show flow to the river in this area.

- **RM 25.5—Well & Gauging Station GR-3**. At this location, 5.5 miles downstream from the USGS stream gage, the Green River gains flow all year. As at GR-1, water level contours for the Qal show flow from the aquifer to the river; however, the water level differences—and thus the flow gradients toward the river—are much larger here. Water level differences are 1 to 7 feet annually.

5.1.1.3 River Flow Measurements

Gains and losses can be assessed by comparing flow rates at various points along a river. If the flow rate measured at a downstream station is higher than it is at an upstream station, the source of the increase must be groundwater (assuming no tributaries or springs occur along the reach). However, to be statistically valid, the difference between the two measured flows must be higher than the errors associated with measuring them; these measurement-related errors are typically 5 to 10 percent of the

[36] Pacific Groundwater Group, 1999. *1999 Hydrogeologic Characterization, City of Aubur*n. Consultants' report prepared for the City of Auburn.

total river flow using USGS standard methods[37]. Green River flow data evaluated in the PGG study were determined by PGG to have an accuracy of 10% based on ratings by the USGS and PGG subconsultants.

For the City of Auburn study, mean monthly flows for the Green River were compared at three stations between RM 25.5 and 35 that the City of Auburn monitored during Water Years 1997 and 1998[38]. Only results for one month for the upper reach between RM 35 and RM 31, ending at the USGS gauge, were within a confidence interval that could be interpreted as either a gain or loss. Between these two locations, and after adjustment for inflow from Big Soos Creek, which was separately gauged, the Green River gained flow within this reach at an average rate of 53 cfs during September 1997. However, since the reported confidence interval range was ±51 cfs (based on error analysis with upstream flow of 335 cfs and downstream flow of 388 cfs), actual gains were likely to have been anywhere between 2 and 104 cfs. For other periods, the errors significantly exceeded the computed change and no conclusions can be made about gains or losses. Likewise, no conclusions can be made regarding gains or losses for the lower reach between RM 25.5 and RM 31.

5.1.2 Upgradient Groundwater Flow Conditions

The groundwater flowing through the Green River Valley and Auburn-Kent Valley originates from a number of upgradient sources within WRIA 9 and WRIA 10. In the Auburn vicinity, groundwater moves downgradient from the Covington, the Federal Way, and to some degree the Enumclaw Uplands until it reaches the valley, where it may discharge to the Green River. These upland areas include layers of high- and low-permeability sediments that produce horizontal and vertical flow components as groundwater moves downward, toward the Green River. A significant amount of groundwater also originates within the valleys as incident precipitation that infiltrates into the permeable sediments and then flows along a path that roughly parallels the river. Additionally, water from the Green River may discharge to the underlying Qal sediments along losing reaches, recharging the aquifer.

A substantial amount of groundwater flows toward the Green River from the neighboring White River Valley (WRIA 10). The groundwater from the White River Valley flows along a shallow alluvial aquifer (Qal) until it reaches the confluence with the Auburn-Kent Valley (Figure 5.1). It then turns—rather sharply—around the western edge of the Enumclaw Upland and follows the Green River northward through the Auburn-Kent Valley. This groundwater, which originates from the White River and the Lake Tapps and Enumclaw Uplands, follows a path that roughly parallels the ancestral channel of the White River to its historical confluence with the Green River at about RM 32—that is, the pre-1906 channel, before a catastrophic flood diverted most of the river's flow into its southern fork, the Stuck River.

The City of Auburn's *1999 Hydrogeologic Characterization Report* states that water from the White River valley Qal alluvial aquifer (and from the White River) enters the combined Qal and Qvrd aquifer in the Auburn-Kent valley at a rate of 31 to 62 cfs. A substantial portion of this water flows north toward the Green River. While it is not known how much of this water discharges to the Green River, the report states that additional pumping in the Qvrd would reduce groundwater discharge to the Green River. Additional detailed modeling would be required to further address this issue and to quantify the seasonal and annual variability in groundwater flows.

---

[37] USGS Office of Surface Water Technical Memorandum No. 93.07, policy statement on stage accuracy dated December 4, 1992, states, "The accuracy of surface water discharge records depends on the accuracy of discharge measurement, the accuracy of rating definition, and the completeness and accuracy of the gage-height record. Accuracies of discharge records for individual days commonly are about 5 to 10 percent.

[38] Pacific Groundwater Group, 1999. *1999 Hydrogeologic Characterization, City of Auburn*. Consultants' report prepared for the City of Auburn.

5.2 Deep & Coal Creek Closed Depression Basins, RM 48-52

The most apparent source of inflow to the Green River along the reach from RM 48–52 is the springs that issue from the upland areas immediately south of the river. Figure 5.2 shows locations of the major springs and assumed recharge areas (the delineated sub-basins). The water level contours on a map presented in a report by Brown & Caldwell map suggest that groundwater flows northwest through a regional aquifer toward the springs[39]. These springs lie along the steep slopes that bound the river valley and discharge into small creeks that eventually join the river. They are located in areas where the steep slopes expose glacial sediments or the interface between relatively unconsolidated glacial sediments and Tertiary bedrock. Four dominant springs flow to the Green River from RM 48–52.

Table 5.1
Major Springs between Green River RM 48 and RM 52

Spring	RM (Approximate)	Flow (cfs) Low	Average	High	Period of Record	Data Source[40]
Icy Creek	48.2	0.9 [1]	23 [2]	78 [3]	1963–68	USGS website
Black Diamond	49.5	5	20	40	---	Penhallegon, 2000[41]
Palmer	49.7	4	10	25	---	Penhallegon, 2000
Resort	51.3	2	---	5	---	Brown and Caldwell, 1989

Notes: 1=mean monthly flow in October 1967; 2=average flow for 1964–1967; 3 = mean monthly flow in February 1965.

5.2.1 Icy Creek

The primary spring that feeds Icy Creek lies at an elevation of about 600 feet, about 0.7 miles upstream of the creek's confluence with the Green River, where WDFW operates a nearby salmon-rearing facility[42]. Seasonal creek flows range widely, according to USGS stream gauge records from the 1960s[43]. Temperatures in the creek range from 6.7°C to 10.6°C degrees seasonally based on King County measurements from July 2001 to August 2002. These seasonal variations in flow and temperature suggest that the creek-spring system is substantially affected by upgradient recharge and local runoff. The recharge area for the Icy Creek spring is suspected to include the adjacent Coal Creek basin, which drains to Fish Lake.

---

[39] Brown & Caldwell, 1989, *Geohydrology Studies of the Metro Section 16 Silvigrow Project, March 1989*.

[40] The relatively-recent sources listed below may have relied on flow data originally published in Appendix Table 11-records of springs from Luzier, J.E., "*Geology and Ground-Water Resources of Southwestern King County, Washington,*" USGS Water-Supply Bulletin No. 28, 1969.

[41] Penhallegon Associates Consulting Engineering, Inc., 2000, *Year 2000 Final Comprehensive Water System Plan*. Prepared for City of Black Diamond.

[42] Washington State Conservation Commission and King County, *Limiting Factors and Reconnaissance Assessment Report for WRIA 9 and Vashon Island*, December 2000.

[43] U.S. Geological Survey, 2004, Washington NWIS Web Data—USGS 12107300 Icy Creek near Black Diamond, WA. Http://nwis.waterdata.usgs.gov/wa/nwis/nwisman/?site_no=12107300&agency_cd=USGS.

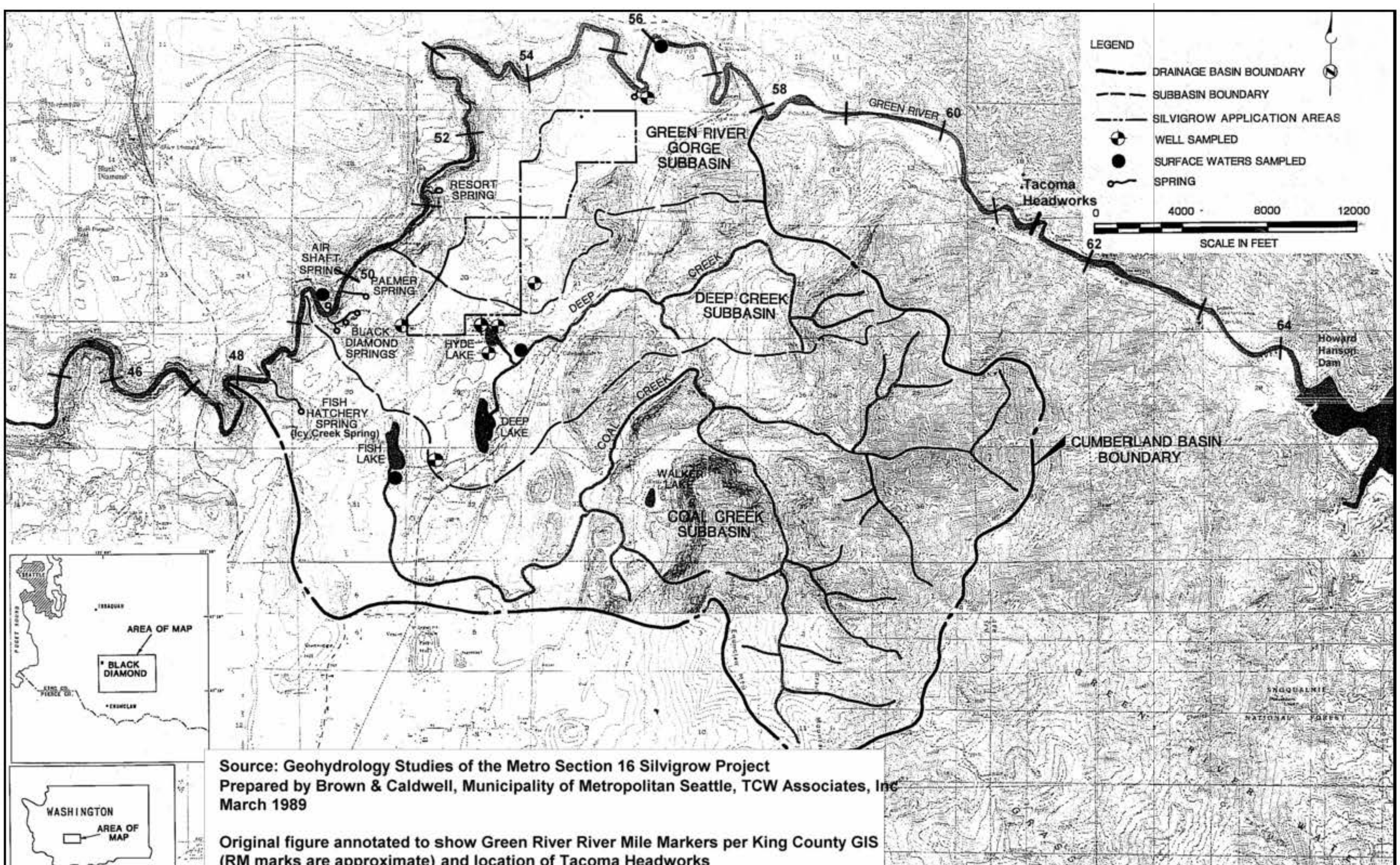


Figure 5.2. Locations of Major Springs

Both local and regional groundwater flow conditions may contribute to Icy Creek spring. Recent drilling on the Franklin Plat above the spring suggests that a highly permeable paleochannel lies in close proximity to the plat, defining a narrow zone of groundwater flow [44]. The site-specific Franklin Plat study reveals how local-scale flow conditions differ substantially from the laterally continuous regional flow conditions of Brown & Caldwell[45]. However, the Franklin Plat study does not address the paleochannel geometry upgradient or downgradient of the plat, nor does it explore the hydraulic connections to the regional flow system.

WDFW uses water from the springs for fish propagation at its salmon-rearing facility. During low-flow periods, the rearing ponds capture all the water flowing from these springs; flow is measured monthly at exit points from the rearing ponds. During seasonal high flows, the piping system into the ponds is incapable of handling the entire spring flows and total flows are estimated. Table 5.2 summarizes recent monthly flows for Icy Creek Springs as reported in the *Limiting Factors Report*[46] which credits the source of these data as S. Mercer (2000) of the Washington Department of Fish and Wildlife. Flows are provided in Table 5.2 in units of both gallons per minute (gpm) and cubic feet per second (cfs). It should be noted that the USGS records of Icy Creek Springs summarized in Table 5.1 suggest monthly flows for Icy Creek Springs which are considerably more variable than the values presented in Table 5.2. As the period of record and frequency of discharge measurements for the Table 5.2 data is unknown; the USGS historical records are considered the more reliable source of data to characterize flows at Icy Creek.

Table 5.2
Recent Monthly Flows in Icy Creek Rearing Ponds and Springs

Month	Low Flow (gpm)	High Flow (gpm)		Low Flow (cfs)	High Flow (cfs)
January	3,700	5,300		8.2	11.8
February	3,700	5,300		8.2	11.8
March	4,000	5,450		8.9	12.1
April	5,300	5,800		11.8	12.9
May	2,800	5,100		6.2	11.4
June	2,800	3,100		6.2	6.9
July	2,500	3,100		5.6	6.9
August	2,600	3,300		5.8	7.3
September	1,100	1,580		2.4	3.5
October	700	915		1.6	2.0
November	1,300	4,500		2.9	10.0
December	3,400	3,900		7.6	8.7

44 Icicle Creek Engineers, Inc., 2002, *Letter Supplement No. 2, Hydrogeologic Consultation, Proposed Subdivision – Franklin Plat, King County, WA*. King County Application No. L01P001, Letter dated September 12, 2002.

45 Brown & Caldwell, 1989, *Geohydrology Studies of the Metro Section 16 Silvigrow Project, March 1989.*

46 Washington State Conservation Commission and King County, *Limiting Factors and Reconnaissance Assessment Report for WRIA 9 and Vashon Island*, December 2000

5.2.2 Black Diamond & Palmer Springs

The Black Diamond Springs actually issue from three locations (south, middle, and north) at an elevation of about 620 feet. The City of Black Diamond operates a collection facility that conveys water from these and the nearby Palmer Springs to its municipal supply system located approximately 2 miles northwest of the Green River. The City has water rights which allow for an instantaneous withdrawal of approximately 8.0 cfs and a mean annual withdrawal of 0.76 cfs from these springs.

5.2.3 Resort Springs

A local community collects a portion of Resort Springs for water supply. No water use data are available for these springs.

5.2.4 Other Springs in vicinity of Green River RM 48-52

An additional source of "spring" water (about 2 cfs) is reported by Brown and Caldwell[47]. This water drains from a coal mine tunnel near Hyde Lake. Another spring—the Air Shaft Spring—discharges from the steep slope on north side of the Green River, approximately at RM 49.6. Other springs undoubtedly flow into creeks that feed the Green River along this reach or they occur as diffuse seepage faces along steep slopes.

[47] Brown & Caldwell, 1989, *Geohydrology Studies of the Metro Section 16 Silvigrow Project, March 1989*.

6 Land Use, Recharge, and Future Land Use Change Analysis

Land use activities have a direct and sometimes dramatic impact on streamflows. In urban areas, the elimination of forest cover, compaction of the surface soils, and placement of impervious surfaces are associated with increased rates and volumes of surface runoff, and with reduced recharge to groundwater. Development activities can also result in increased stream temperatures due to reduced groundwater-derived base flows and to loss of shading along riparian corridors. This chapter provides an assessment of the extent and magnitude of the existing and planned urbanization of the Lower/Middle Green River basin. Also, the findings of recent studies on groundwater recharge in the study area are reviewed. The analysis presented here does not specifically quantify the effects of land use activities on streamflows and temperatures but does provides data which are relevant to such an analysis. The location and magnitude of planned future development is assessed relative to current conditions so as to provide an indicator of potential impacts to groundwater recharge and to streamflows.

6.1 Soils and Land Use Data

All Geographic Information System (GIS) soils and land use datasets used in the land use assessment were obtained from others. The source data sets are summarized below. All datasets obtained from King County used the Washington State Plane-North Zone-NAD1983/HARN coordinate system. Datasets obtained from other sources, which used alternative coordinate systems, were converted to the King County standard.

- Existing land cover was based on 1998 LANDSAT imagery with classifications performed by Hill et al[48]. The dataset is in a raster format with 30-meter pixel size characteristic of the LANDSAT imagery. The land cover classification used seven categories of land cover that were derived for use in urban and urbanizing watersheds. NHC acquired the dataset directly from the author's webpage at the University of Washington Center for Water and Watershed Studies, then re-projected from UTM-zone 10 NAD 1927 coordinate system to the project coordinate system of Washington State Plane-North Zone-NAD 1983/HARN.

- Future land cover was based mainly on land use zoning data compiled in GIS format by the Puget Sound Regional Council (PSRC). The PSRC dataset includes comprehensive plan data for all incorporated and unincorporated areas of Pierce, King, Kitsap and Snohomish Counties. The dataset was acquired from the PSRC in the Washington State Plane-North Zone-NAD 1983 coordinate system and transformed to the NAD 1983/HARN datum.

- Sensitive areas, which are assumed to be protected from future development, were identified from wetland and open water datasets (WETLD and WTRBDY) obtained from King County. County-wide datasets describing other sensitive areas (steep slopes, coal mine hazards, etc.) were not available.

- Groundwater recharge areas were identified primarily from a GIS layer provided by King County (RECHARGE) which characterizes land areas as low to high recharge potential based on the County's analysis of surficial geology, soils and depth to groundwater.

[48] Hill, Kristina; Botsford, Erik; Booth, Derek. 2000. A Rapid Land Cover Classification Method for Use in Urban Watershed Analysis. Center for Urban Water Resource Management (Now the Center for Water and Watershed Studies) at the University of Washington. October 6th, 2000

- A supplemental source of groundwater recharge information was a dataset titled SURFGEOL, produced by Booth et al.[49] and which characterizes the surficial geology of the entire county. This supplemental information was used for areas of zoned urban development which were beyond the limits of the RECHARGE dataset.

Because the LANDSAT imagery was not available in a shape file format, all data layers were transformed to a common 1-meter grid format for purposes of computations and subsequent displays. The original 30-meter grid from the LANDSAT imagery was felt to be too coarse to use in overlays with watershed boundary and other data layers, and the 1-meter grid was felt to provide appropriate resolution.

Land use classifications from the LANDSAT dataset of future conditions were reclassified to approximate land cover percentages as shown in Table 6.1. Land zoning classifications from the PSRC dataset representing future conditions were aggregated and reclassified to approximate land cover percentages as shown in Table 6.2. Note that High Density Residential land use is defined in this study as all residential densities greater than 4 dwelling units per acre (du/ac), including multi-family densities having more than 7 du/ac. This aggregation was needed because large portions of the urban growth areas in the Green River Study Area are zoned in the PSRC dataset for a residential density of between 4 and 12 du/ac, and does not distinguish between single family and multi-family densities.

The source PSRC dataset of land use zoning included hundreds of discrete zoning classifications. Consolidation of the information into common groupings was performed by looking up the planning data for individual municipalities to decipher planning descriptions. For some areas the planning descriptions do not give any indication of the land cover that may exist in the developed state (i.e. Government, Military, Tribal and Public). In those areas the existing landcover pixels from the LANDSAT classification were incorporated into the PSRC dataset and aggregated using best professional judgment into the categories in Table 6.2.

Table 6.1
1998 LANDSAT Classification Categories and Land Cover*

LANDSAT Classification	Land Cover Percentages				
	Open Water	Trees	Shrubs/Grass	Pavement (TIA)	Bare Earth
Urban Forested (UF)	0	39	23	38	0
Urban Grass Shrub (UG)	1	4	21	73	1
Urban Paved (UP)	1	5	2	92	0
Forested (FOR)	0	96	1	1	2
Grass Shrub Crops (GR)	0	1	94	3	2
Water (WAT)	100	0	0	0	0
Bare Soil (SOIL)	1	2	0	7	90

*Based on orthophoto verification by Hill et al.

[49] Booth, D.B., R.A. Haugerud, and J. Sacket, in review, Geologic map of King County, Washington: U.S. Geological Survey Miscellaneous Investigations Map, scale 1:100,000.

Table 6.2
PSRC Aggregated Zoning Categories and Land Cover

Aggregated Land Use Category based on PSRC Zoning	Land Cover Percentages						
	Forest	Agric/ Pasture	Grass	EIA*	TIA*	Wetland	Open Water
Lakes / Open Water (OW)	0	0	0	0	0	0	100
Designated Wetlands (WET)	0	0	0	0	0	100	0
Industrial Forest (IND FOR): Roaded timber production	99.5	0	0	0.5	1	0	0
Open Grass (OG): Parks and recreational space	0	0	100	0	0	0	0
Mineral Resource Lands: Quarries and mines	0	0	50	50	50	0	0
Agricultural lands (AG)	0	99	0	1	1.3	0	0
Low Density Residential (LDR): < 1 d.u. per acre	0	48	48	4	10	0	0
Medium Density Residential (MDR): 1-3 d.u. per acre	0	0	86	14	25	0	0
High Density Residential (HDR): >4 d.u. per acre	0	0	60	40	53	0	0
Commercial (COM): comer-cial, industrial, road corridors.	0	0	14	86	90	0	0

* EIA is Effective Impervious Area, representing the surface from which runoff is conveyed directly to an improved conveyance system with limited opportunity for infiltration to groundwater. EIA summed with other land covers, excluding TIA, yields 100% of the land area. TIA is Total Impervious Area presented for consistency with the classifications for the current conditions LANDSAT imagery. TIA percentages duplicate other categories and should not be summed with the other future land use components.

Figures 6.1 and 6.2 respectively show the current conditions and the land use zoning. Land use conditions for current and future (zoned) conditions for each of the study area sub-basins were tabulated with a 1-meter grid using ArcView GIS and are summarized in Tables 6.4 and 6.5. Figures showing the current land use of the areas zoned for urban and commercial development, and overlays showing groundwater recharge classifications, are provided as part of the land use change analysis in Section 6.4.

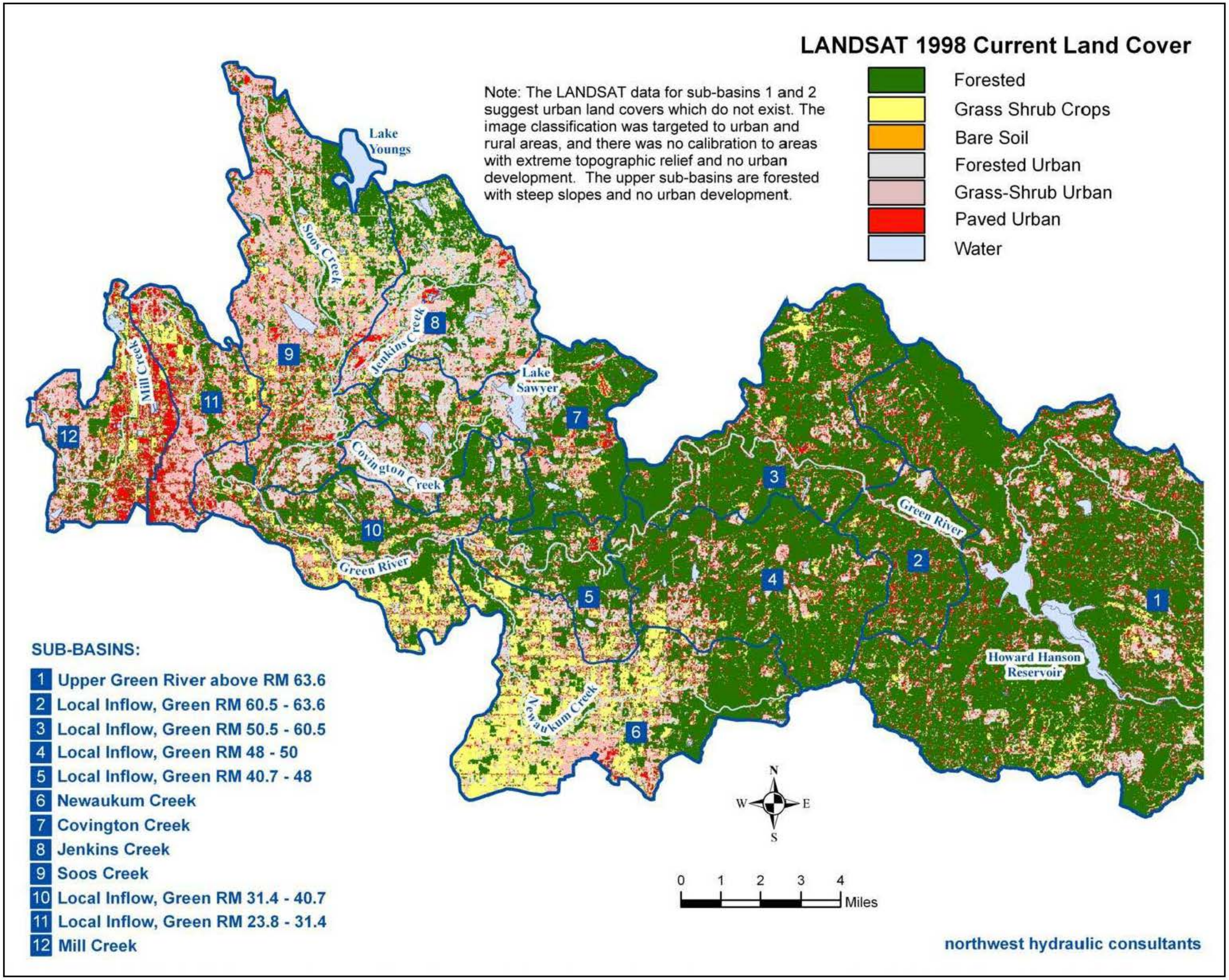


Figure 6.1. Current Land Cover from 1998 Landsat Satellite Image

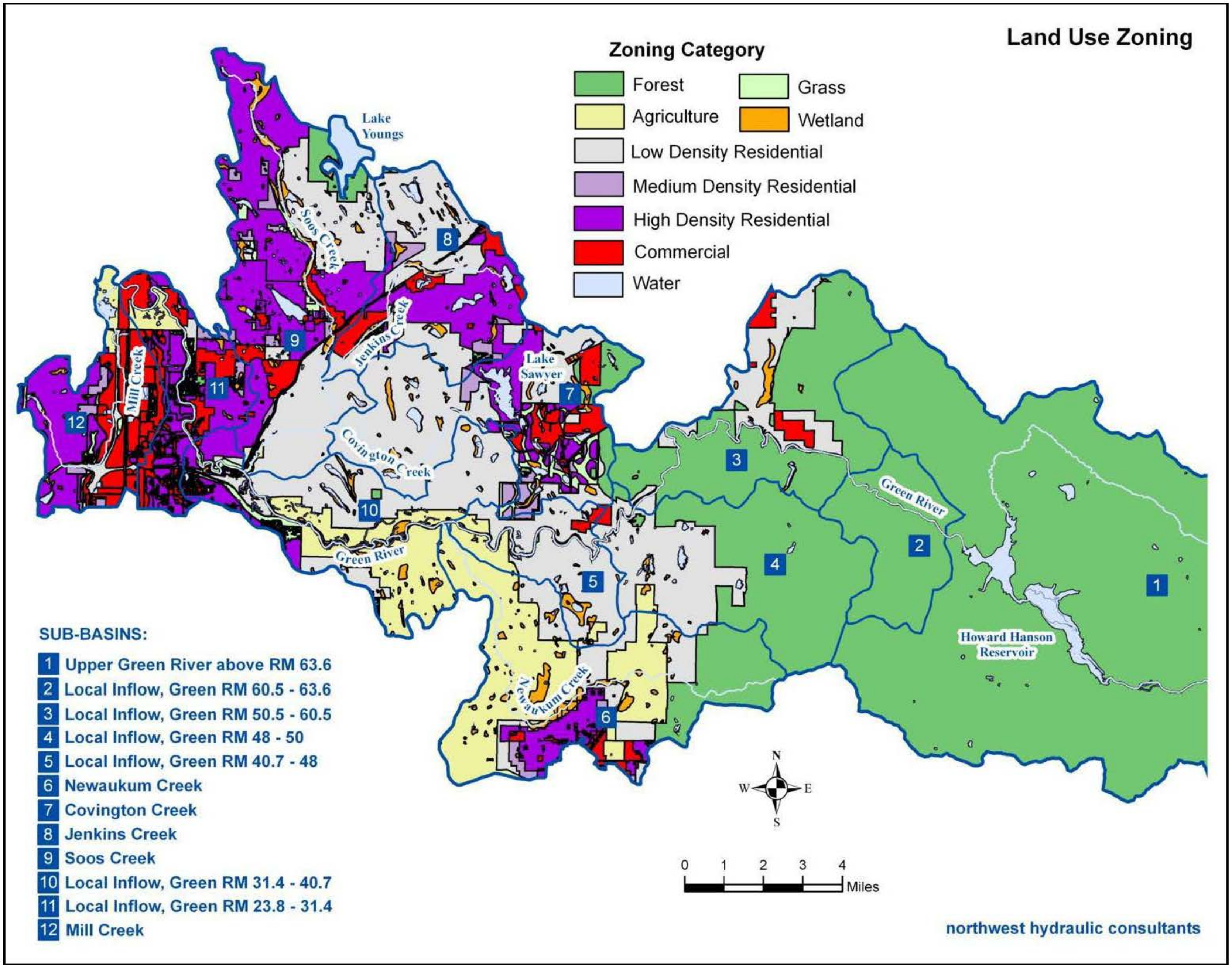


Figure 6.2. Land Use Zoning—Future Land Cover Conditions

Table 6.3
Sub-Basin Current Conditions Land Cover

Sub-Basin		Total Area (sq. mi.)	LANDSAT Classification (%)							TIA:**
ID	Name		Forest Urban	Grass Shrub Urban	Paved Urban	Forest	Grass Shrub Crops	Water	Bare Soil	Total Impervious Area, %
1*	Upper Green River above RM 63.6	222	0	0	0	92	8	0	0	1
2*	Local Inflow, Green RM 60.5 – 63.6	9.4	0	0	0	96	4	0	0	1
3	Local Inflow, Green RM 50.0 – 60.5	22.2	12	3	1	79	5	0	0	8
4	Local Inflow, Green RM 48 – 50	21.5	13	3	0	77	6	0	0	9
5	Local Inflow, Green RM 40.7 – 48	8.6	18	9	2	58	12	0	0	16
6*	Newaukum Creek	27.1	12	5	2	36	45	0	0	11
7	Covington Creek	21.5	25	10	2	52	7	2	1	20
8	Jenkins Creek	15.9	34	20	3	33	8	1	1	31
9	Soos Creek	29.0	24	27	3	31	13	1	1	33
10	Local Inflow, Green RM 31.4 – 40.7	20.2	18	14	2	46	20	0	0	20
11	Local Inflow, Green RM 23.8 – 31.4	10.0	14	32	14	19	20	0	1	42
12	Mill Creek	12.3	17	25	17	17	20	0	3	42

* An initial evaluation of the satellite data identified erroneous results for sub-basins 1, 2, and 6, based on a subsequent comparison to zoning and USGS maps. The following adjustments were made to the data. In sub-basins 1 and 2, which are both forested basins with no urban development, all areas initially categorized from the satellite image as urban forest and urban shrub were respectively reclassified as (non-urban) forest and shrub. In sub-basin 6 which is a predominantly agricultural basin, 2/3 of the area initially categorized from the satellite image as urban shrub was reclassified as (non-urban) shrub/crops. Table 6.3 above presents the values after these adjustments were applied.

** Note that the TIA values presented above are derived from classification methods which were calibrated to urbanized basins. Comparison with the Table 6.4 future TIA values derived from zoning data suggests that the values in Table 6.3 above may be too high in the non-urban basins. Non-urban basins are those with significant forest cover, agricultural land use, and low-density residential development.

Table 6.4
Sub-Basin Zoning: Future Conditions Land Use

Sub-Basin		Total Area (sq. mi.)	Aggregated Land Use from PSRC Zoning (%)									TIA (%)
								RESIDENTIAL				
ID	Name		OW	WET	IND FOR	GR	AG	LD	MD	HD	COM	
1	Upper Green River above RM 63.6	222	1	0	99	0	0	0	0	0	0	1
2	Local Inflow, Green RM 60.5 - 63.6	9.4	1	0	99	0	0	0	0	0	0	1
3	Local Inflow, Green RM 50.0 - 60.5	22.2	1	2	72	0	0	21	0	0	4	6
4	Local Inflow, Green RM 48 – 50	21.5	1	1	65	0	1	31	0	0	1	4
5	Local Inflow, Green RM 40.7 – 48	8.6	3	5	1	1	15	72	1	0	3	10
6	Newaukum Creek	27.1	0	5	18	0	46	17	2	8	2	9
7	Covington Creek	21.5	3	5	8	6	0	53	4	12	9	21
8	Jenkins Creek	15.9	2	6	1	0	0	48	5	31	8	32
9	Soos Creek	29.0	1	6	4	2	0	34	3	43	5	34
10	Local Inflow, Green RM 31.4 - 40.7	20.2	2	5	1	4	33	43	2	8	1	11
11	Local Inflow, Green RM 23.8 - 31.4	10.0	2	2	3	4	7	6	7	42	28	51
12	Mill Creek	12.3	1	3	1	4	6	10	5	36	34	54

Land Use Definitions are per Table 6.2 as follows: OW = Open Water; WET = Designated Wetlands; IND FOR = Industrial Forest with Roads; GR = Grass; AG = Agricultural Lands; LDR = Low Density Residential at < 1 d.u. per acre; MDR = Medium Density Residential at 1-3 d.u. per acre; HDR = High Density Residential at >4 d.u. per acre (including Multi-Family densities); and COM = commercial, industrial, airport, and transportation corridors. TIA is Total Impervious Area.

A land use change analysis, which examines the existing condition of lands zoned for urban and commercial development, is presented in Section 6.3.

6.2 Recharge Analysis

Groundwater quantities are strongly influenced by the recharge process, the mechanism that replenishes groundwater with water derived from precipitation. Factors influencing recharge include precipitation, soil type and surficial geology, and land cover. The highest rates of recharge occur in areas where precipitation is high, soils are coarse, and evapotranspiration rates are low. For example, precipitation falling on coarse soils will recharge at much higher rates than it will in urban areas covered with pavement, which is impervious and facilitates runoff. Recharge may also be higher in higher-elevation areas, which generally receive more precipitation.

For this assessment, the results of two previous regional studies were used to estimate annual volumes of recharge within each sub-basin. Average annual recharge is an important parameter to quantify because it is used in water-budget analyses. The regional recharge studies are discussed in Section 6.2.2; estimates of average annual recharge are presented in Section 6.2.3.

6.2.1 Precipitation and Runoff Amounts

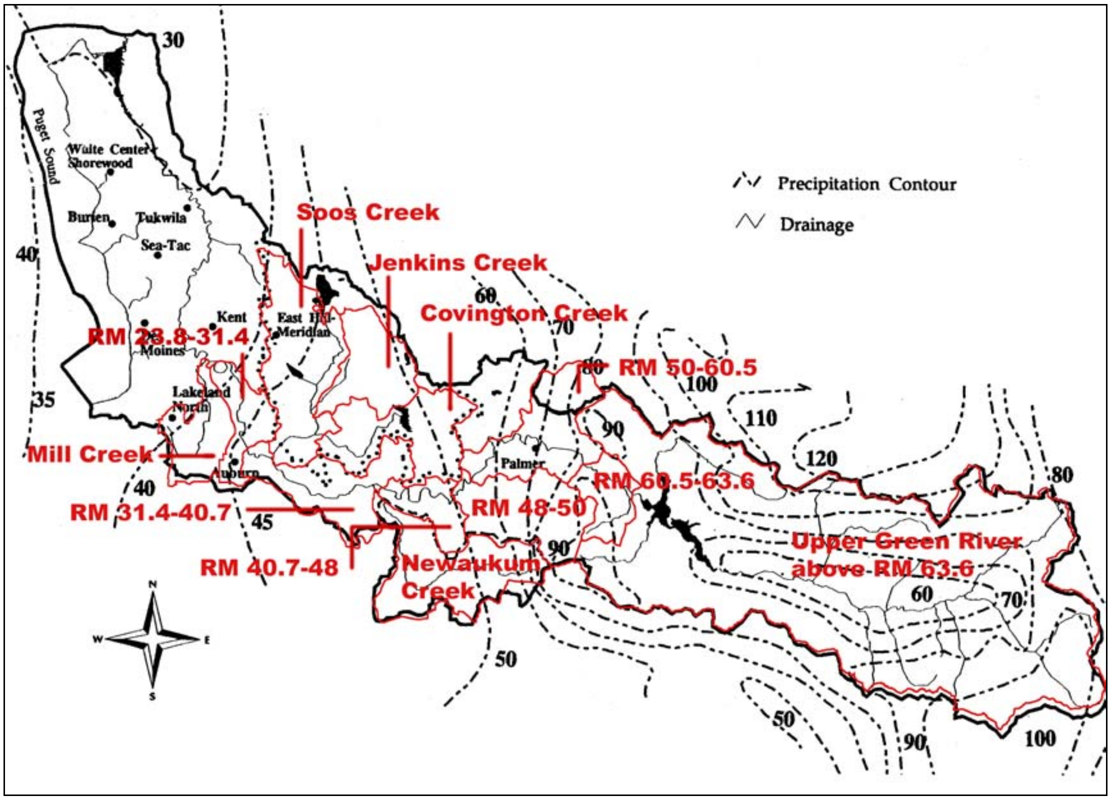
Annual precipitation in the Green River study area ranges from over 90 inches in areas feeding the upper reaches of the Green River to less than 30 inches in the lowlands near Puget Sound, north of White Center. Figure 6.3 shows precipitation contours and basin boundaries. The highest precipitation values occur within the northern portion of the Upper Green River sub-basin and within bordering sub-basins (RM 48–50, RM 50–60.5, and RM 60.5–63.5). These areas generally correspond to higher elevations; precipitation values above Howard Hanson Dam reflect the higher elevations of the uplands and Cascades that rise above the Green River canyon floor. Precipitation values of 40 to 50 inches per year dominate much of the WRIA west of Palmer.

Runoff, or the amount of precipitation that reaches streams, has been coarsely estimated with water balance methods (runoff = precipitation minus evapotranspiration) to range from nearly 80 inches per year in portions of the upper Green River basin to about 25 inches per year in the lower watershed near Auburn. Figure 6.4 adapted from Richardson et al.[50] shows runoff contours for the portions of south King County, including the Green and Cedar River Basins. The runoff amounts combine all components of basin drainage, including both surface runoff and groundwater flows.

---

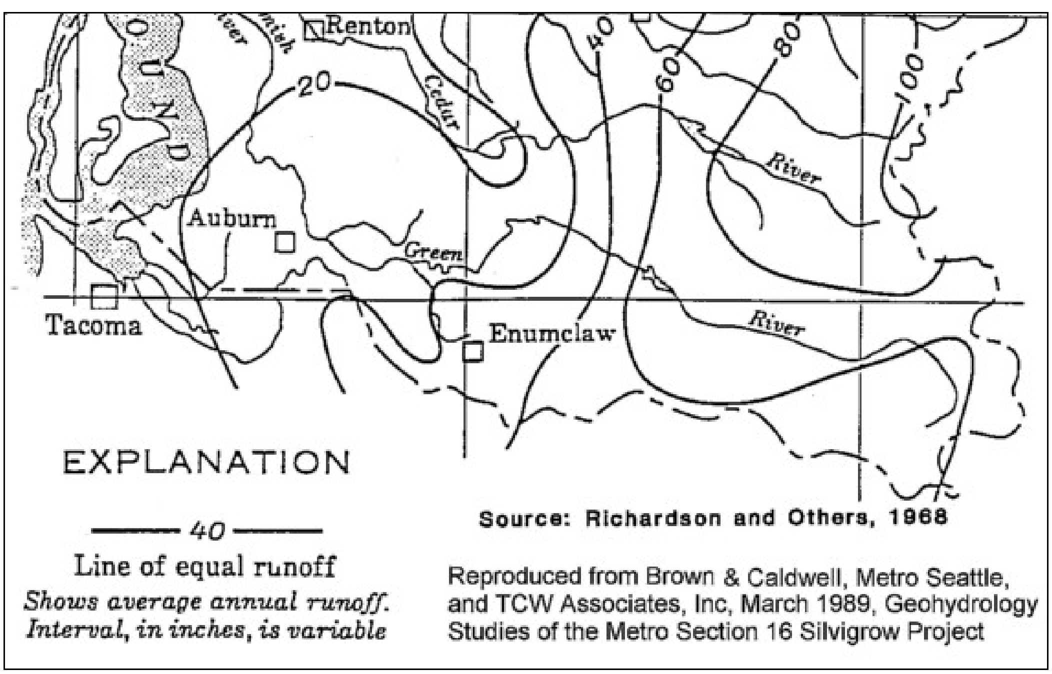
[50] Richardson, D., Bingham, J.W., and Madison, R.J., "*Water Resources of King County, Washington,*" USGS Water-Supply Paper 1852, 1968.

Figure 6.3
Precipitation Contour Map for Green River Study Area



Map modified from a figure in Ecology's 1995 Initial Watershed Assessment for WRIA 9.

Figure 6.4
Runoff Contour Map for Portions of South King County



6.2.2 Recharge Distribution by Gridded Water Balance Models

Two previous studies have assessed the spatial distribution of recharge in the study area. The USGS computed the average annual recharge rate for each quarter-quarter section within King County using a deep percolation model (DPM)[51] and regression equations. These data, which are available in GIS digital format, were used to create Figure 6.5 for this assessment. Data from the City of Auburn was also used; the City's data include annual recharge rates for 400-square-meter grid cells over an area covering parts of WRIA 9 and 10[52]. The Auburn data were not available in GIS format. Instead, a digital PDF version of the color-coded, discretized recharge map from the hard-copy report was used in this analysis. This map was imported into the GIS file; road intersections were then matched to those in the GIS file.

Figure 6.5 shows the extent of data coverage in the study area; in general, recharge rates were calculated only for sub-basins downstream of RM 48 as part of the USGS and Auburn studies. Little or no data are available for four sub-basins—RM 48 to 50, RM 50 to 60.5, RM 60.5 to 63.6, or Upper Green River above RM 63.6—and only the western half of the Newaukum Creek sub-basin was covered.

As described by the USGS[53], the DPM, a grid-based model, computes daily deep percolation below the root zone for each cell within a basin and then accumulates these values to estimate monthly, annual, and long-term average annual values. It simulates the physical processes that control recharge rates, including soil-moisture accumulation, evaporation from bare soil, plant transpiration, surface water runoff, snow accumulation and melt, and the accumulation and evaporation of intercepted precipitation. The DPM also accounts for daily changes in soil moisture, plant interception, and snowpack, as well as deep percolation below the root zone when soil moisture exceeds field capacity. The DPM model was used to simulate recharge only in the Soos Creek basin; recharge in other areas was estimated through simple, two-parameter regression equations

Auburn's recharge analysis by PGG was similar to that of the USGS, but it considered 16 land use types (based on 1995 satellite data), whereas the USGS considered only six. For example, the PGG land use types included "low-intensity development" and "medium-intensity development" which were not used in the USGS analysis. Each land use type requires different coefficients for infiltration, runoff, evapo-transpiration, and other parameters. The City of Auburn modified the USGS equations for some land uses, as described in its 1999 hydrogeologic characterization report[54].

It should be recognized that PGG (for the City of Auburn) and the USGS used different regression equations and different assumptions in developing estimates of recharge. One important difference is in recharge estimates for Group D soils and lakes: PGG assigned a recharge rate of 13.6 inches per year to these features while the USGS assigned a rate of zero.[55]

---

[51] Bauer, H.H, and Vaccaro, J.J., 1987. *Documentation of a deep percolation model for estimating ground-water recharge*. U.S. Geological Survey Open-File Report 860536.

[52] Pacific Groundwater Group, 1999. *1999 Hydrogeologic Characterization, City of Aubur*n. Consultants' report prepared for the City of Auburn.

[53] Woodward, D. G., E A. Packard, N. R Dion, and S. S. Sumioka, *Occurrence and Quality of Ground Water in Southwestern King County, Washington,* USGS Water-Resources Investigations Report 92-4098, 1995.

[54] Pacific Groundwater Group, 1999. *1999 Hydrogeologic Characterization, City of Aubur*n. Consultants' report prepared for the City of Auburn.

[55] Ibid.

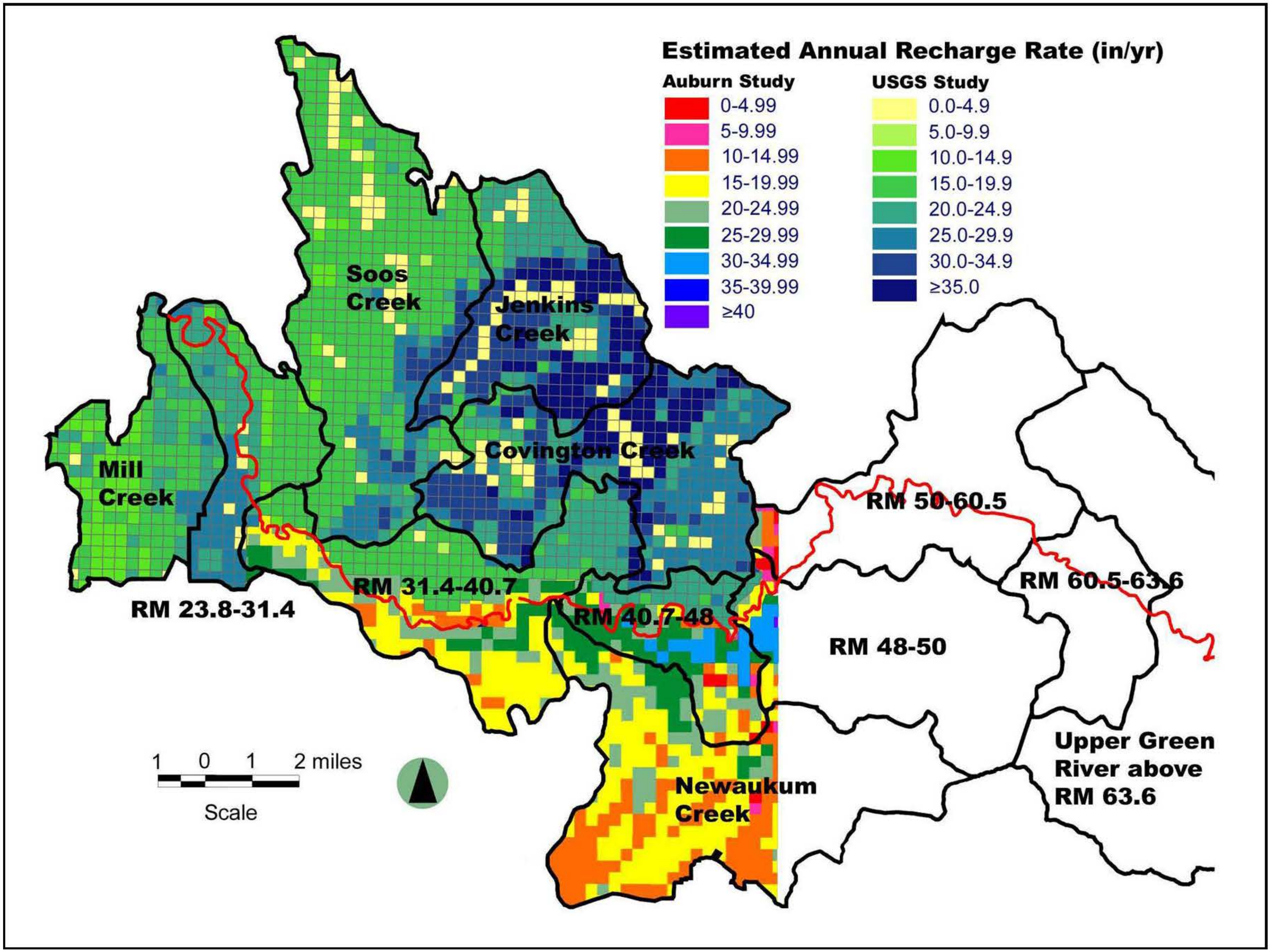


Figure 6.5. Distribution of Average Annual Recharge Rates in Green River Study Area

6.2.3 Average Annual Recharge by Sub-Basin

Table 6.5 summarizes the average annual recharge rate for each sub-basin in the study area. It also shows the percentage of each sub-basin covered under either the Auburn or USGS study. Average recharge was not calculated if either of the two studies covered less than 5 percent of a sub-basin. The values are the best available estimates from published reports of recharge using current analytic techniques.

Table 6.5
Summary of Average Recharge Values by Sub-Basin

ID	Sub-Basin	Average Recharge (in/yr)			Percent of Basin Covered by…	
		USGS	Auburn	Combined	USGS	Auburn
1	Upper Green River above RM 63.6	--	--	--	0	0
2	Local Inflow, Green RM 60.5 - 63.6	--	--	--	0	0
3	Local Inflow, Green RM 50.0 - 60.5	--	--	--	0	<5
4	Local Inflow, Green RM 48 – 50	--	21.5	--	0	9
5	Local Inflow, Green RM 40.7 – 48	21.1	22.7	22.3	23	77
6	Newaukum Creek	--	16.8	--	0	69
7	Covington Creek	26.1	--	--	100	0
8	Jenkins Creek	26.0	--	--	100	0
9	Soos Creek	17.4	--	--	100	0
10	Local Inflow, Green RM 31.4 - 40.7	19.7	17.8	18.6	46	54
11	Local Inflow, Green RM 23.8 - 31.4	20.0	--	--	100	0
12	Mill Creek	18.0	--	--	100	0

Different methods were used to calculate these values, depending on the source data. For the USGS data, a GIS-based approach was used to calculate the average annual recharge rate. After sub-basin boundaries were incorporated into the GIS data, volumetric recharge was calculated for each grid total or partial cell by multiplying rate times area; these volumes were then added and the resulting sum was divided by the area of the entire sub-basin.

GIS coverages were unavailable for the Auburn data. Areas with Auburn recharge data but no USGS data were identified by overlaying the basin boundaries and the USGS recharge coverage on the Auburn recharge map. For each color on the recharge map, cells were counted and an average recharge rate was calculated manually. Although the colors on the Auburn recharge map represented a range of recharge values, the middle value was used for this analysis.

Figure 6.5 and Table 6.5 show that, of the sub-basins covered in this analysis, Jenkins and Covington Creek have the highest recharge rates—greater than 25 in/yr. These sub-basins are characterized by substantial areas of coarse surficial deposits that receive 45 to 65 inches of rain annually (Figure 6.3).

In contrast, the Soos Creek, Mill Creek, and Newaukum Creek sub-basins have the lowest average recharge, all equal or less than 18 inches per year. The Soos and Mill Creek sub-basins feature relatively lower precipitation, low-permeable glacial till, and substantial urban development (impervious surfaces). In the relatively rural Newaukum Creek sub-basin, substantial areas of relatively impermeable mud deposits from the Osceolla mudflow occur at land surface or shallow depths, limiting recharge.

6.3 Land Use Change Analysis

Current land cover conditions were compared to the land use zoning to assess the future land use changes that could occur under the current zoning in the Lower/Middle Green River sub-basins. Sub-basin land use data were presented in Tables 6.3 and 6.4 in Section 6.1. The approach to the land use change analysis assumes that future conversions will be dominated by urban development as allowed under current land use zoning, and that no significant conversions will occur in areas zoned for agricultural or forest use. This approach is superior to a direct comparison of Tables 6.3 and 6.4 because it focuses attention on those areas where significant new impervious cover is likely to occur and can be estimated with a relatively high degree of certainty. As noted previously, the satellite-derived estimates of impervious cover in non-urban portions of the study area were suspiciously high.

Figures 6.6, 6.7, and 6.8 respectively show the extent and current condition of lands which are zoned for urban-density residential, rural residential, and commercial development. Figure 6.6 shows the areas zoned for medium and higher residential development (more than 1 du/ac) including multi-family zones. Figure 6.7 shows the areas zoned for low density (rural) residential with less than one dwelling unit per acre. Figure 6.8 shows the areas zoned for commercial and industrial use. In each case, color coding shows the current condition of the land cover based on the satellite imagery. Areas which are currently developed with urban characteristics are shown in green; areas which are presently in pasture or agricultural uses are shown in pink, and areas which are presently forested are shown in red.

The land use change analysis excludes the green-shaded areas shown on Figures 6.6 through 6.8 because those areas are already developed and any future changes to the land cover are expected to be minor. The red and pink shades show where the new development is planned on currently-pervious lands including forest, open grass, and bare soils, and where the significant land use changes are projected to occur.

Table 6.6 summarizes the results of the land use change analysis.

Table 6.6
Land Use Change Analysis
Forest, Grass, and Bare Soil Areas Zoned for Residential and Commercial Development

Sub-Basin		Pervious Area Zoning area in square miles				Resulting Additional TIA* (sq. mi.)
ID	Name	LDR	MDR	HDR	COM	
1	Upper Green River above RM 63.6	0	0	0	0	0
2	Local Inflow, Green RM 60.5 – 63.6	0	0	0	0	0
3	Local Inflow, Green RM 50.0 – 60.5	3.64	0	0	0.74	1.03
4	Local Inflow, Green RM 48 – 50	5.10	0	0	0.11	0.61
5	Local Inflow, Green RM 40.7 – 48	4.51	0.07	0	0.14	0.59
6	Newaukum Creek	2.76	0.30	0.92	0.24	1.05
7	Covington Creek	6.38	0.56	1.09	1.16	2.40
8	Jenkins Creek	3.87	0.21	1.33	0.35	1.46
9	Soos Creek	5.28	0.35	3.64	0.75	3.22
10	Local Inflow, Green RM 31.4 – 40.7	5.88	0.16	0.54	0.02	0.93
11	Local Inflow, Green RM 23.8 – 31.4	0.23	0.21	1.30	1.10	1.75
12	Mill Creek	0.54	0.36	1.40	1.46	2.20
1-12	Entire Study Area	38.19	2.22	10.22	6.07	15.25

*TIA percentages for LDR, MDR, HDR, and COM are 10, 25, 53, and 90 respectively

The land use change analysis was refined to categorize the areas of new urban development according to groundwater recharge potential. As discussed in Section 6.1, the groundwater recharge dataset from King County classifies the study area into regions of high and lesser recharge rates. Generally, gravelly outwash soils are classified as having a high recharge rate, and fine-grained till soils are classified as having a low recharge rate. From the perspective of urban stormwater management, areas with low infiltration rates and are not suitable for infiltration of urban stormwater runoff.

Table 6.7 summarizes the recharge potential of the areas zoned for new urban development. Figure 6.9 shows the groundwater recharge potential for the areas of new urban development. Green shading is used to designate areas with high infiltration rates and associated high groundwater recharge. Red shading is used to designate areas presumed to have low infiltration rates. As will be discussed later under management options, land use impacts on basin hydrology in the high recharge zones may be mitigated through the use of stormwater infiltration systems and Low Impact Development techniques.

Table 6.7
Groundwater Recharge Potential of
Pervious Areas Zoned for Development

Sub-Basin		Pervious Areas Zoned for Development		
		Total Area	High Recharge Zone	
ID	Name	sq. mi.	sq mi	%
1	Upper Green River above RM 63.6	0	n/a	n/a
2	Local Inflow, Green RM 60.5 - 63.6	0	n/a	n/a
3	Local Inflow, Green RM 50.0 - 60.5	4.4	2.5	58%
4	Local Inflow, Green RM 48 – 50	5.2	4.6	88%
5	Local Inflow, Green RM 40.7 – 48	4.7	2.9	60%
6	Newaukum Creek	4.2	1.4	33%
7	Covington Creek	9.2	3.6	39%
8	Jenkins Creek	5.8	2.4	41%
9	Soos Creek	10.1	3	30%
10	Local Inflow, Green RM 31.4 - 40.7	6.6	3	45%
11	Local Inflow, Green RM 23.8 - 31.4	2.7	1.6	59%
12	Mill Creek	3.7	2.4	67%
1-12	Entire Study Area	56.6	27.4	49%

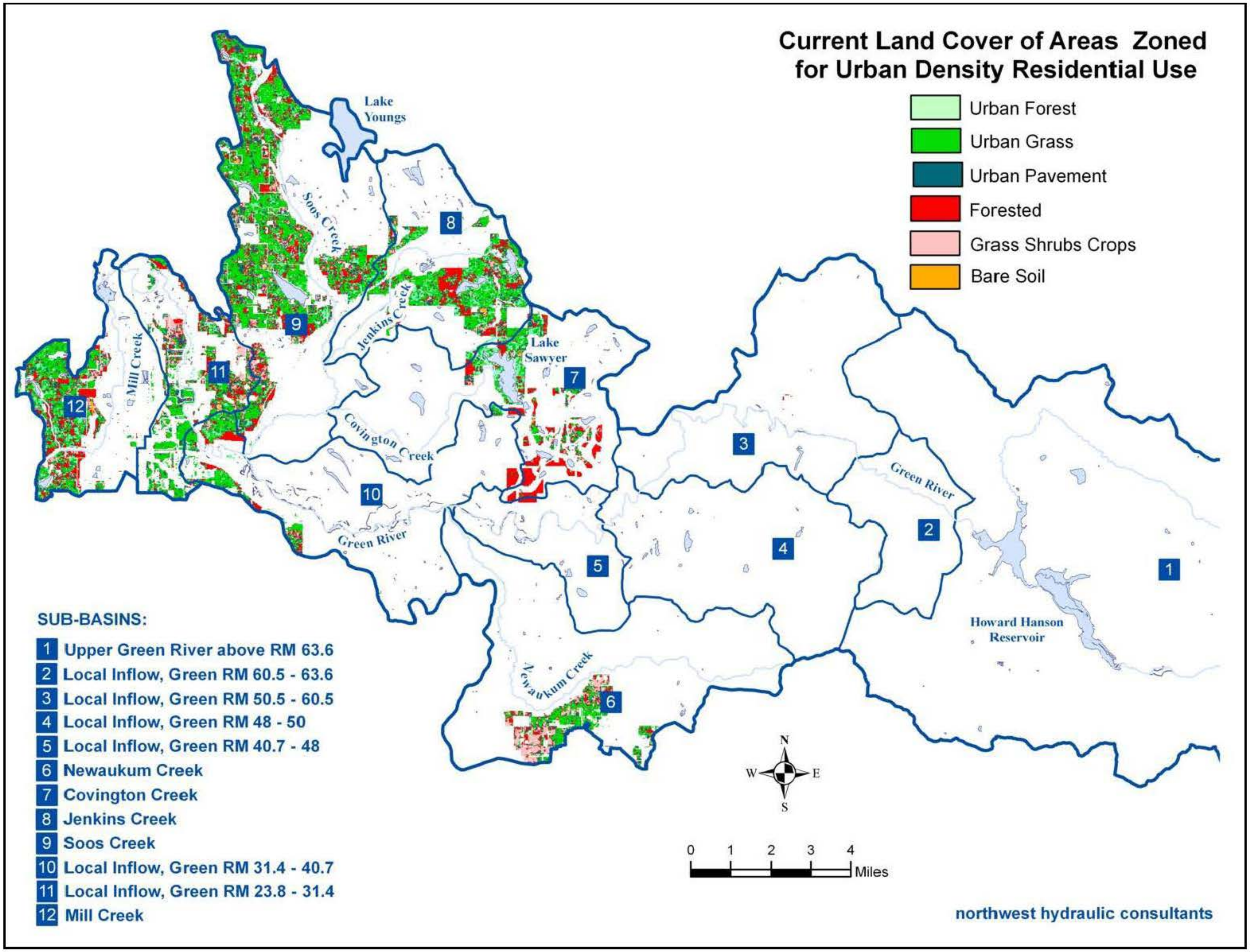


Figure 6.6. Current Land Cover of Areas Zoned for Urban Density Residential Use

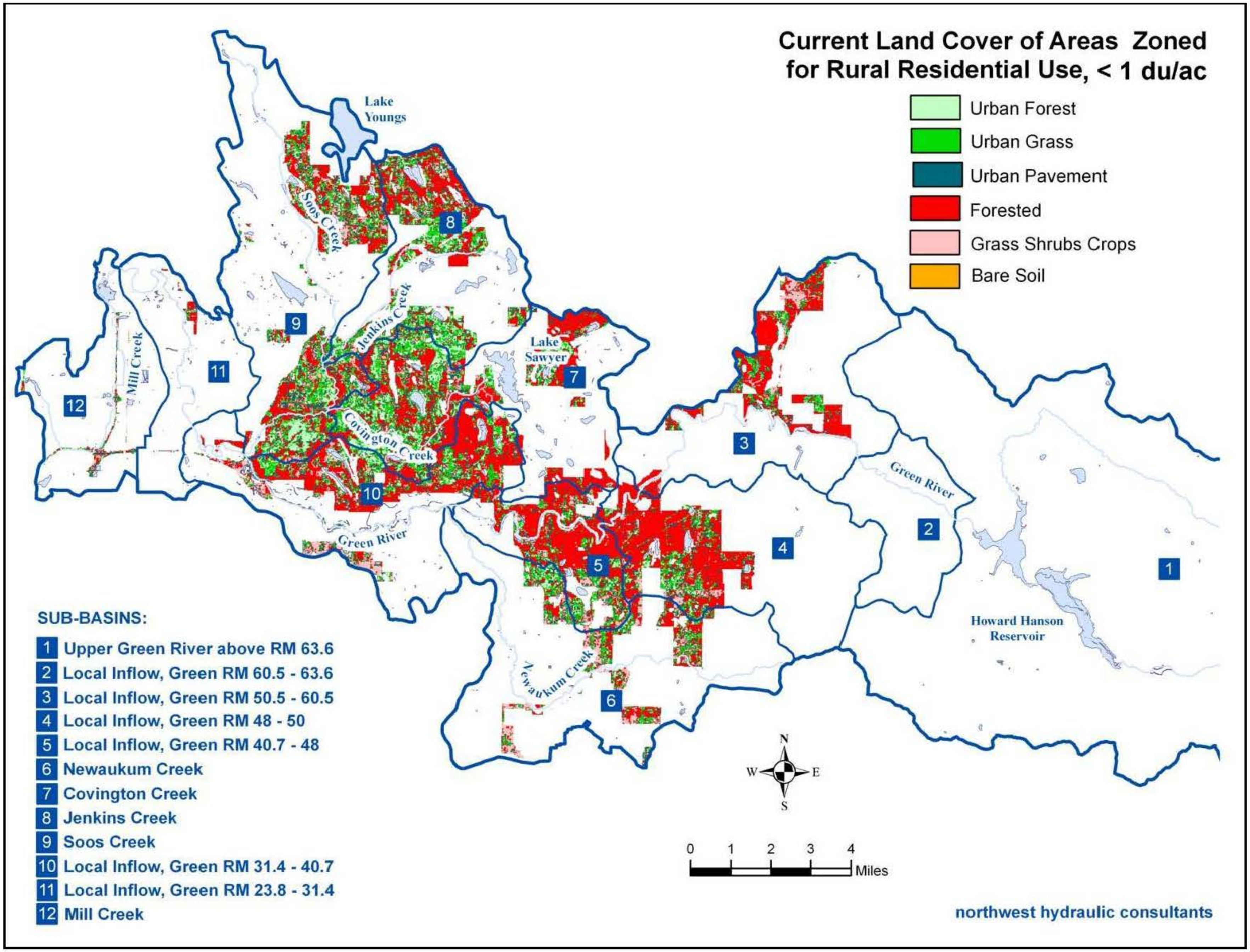


Figure 6.7. Current Land Cover of Areas Zoned for Rural Residential (< 1 du/ac) Land Use

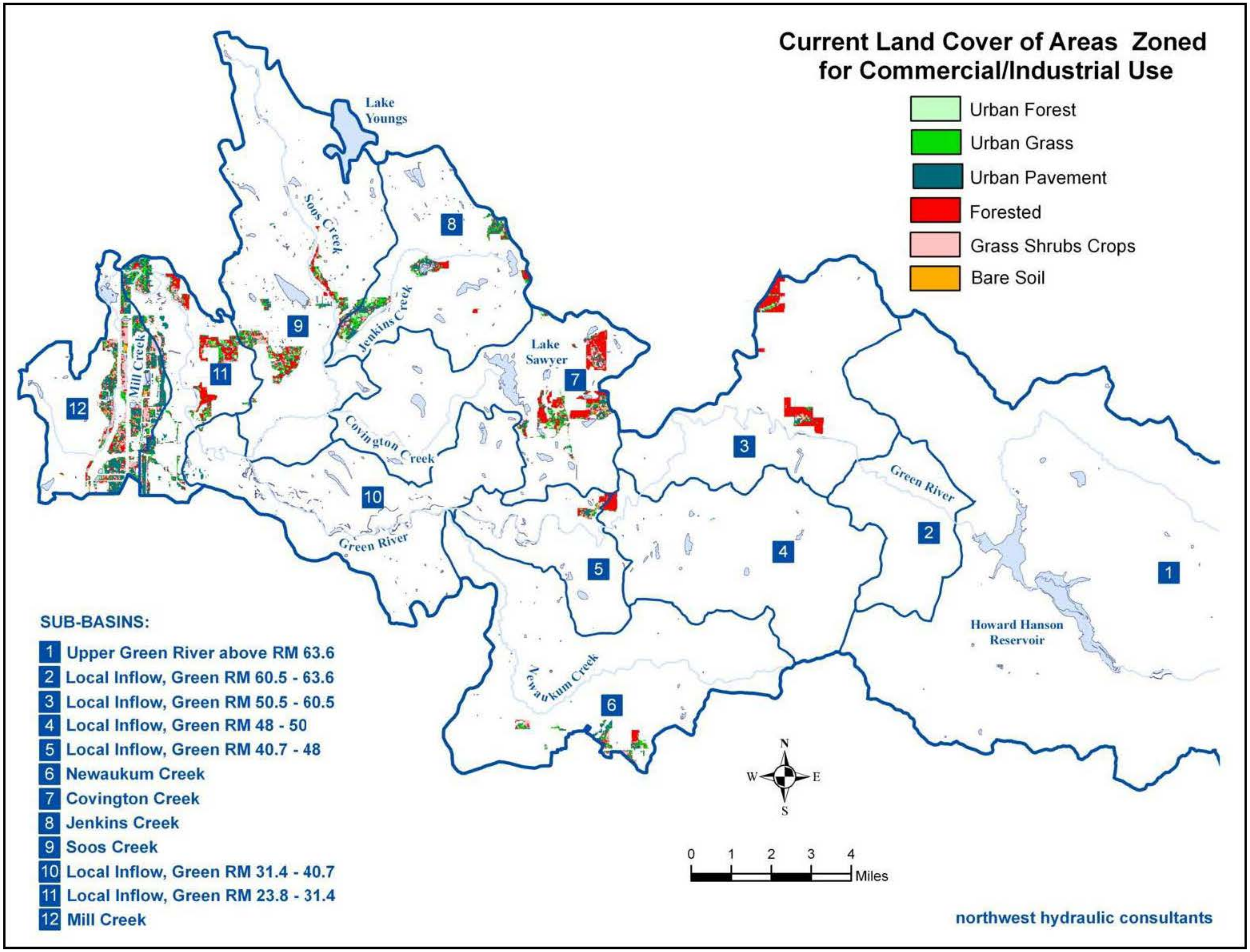


Figure 6.8. Current Land Cover of Areas Zoned for Commercial/Industrial Land Use

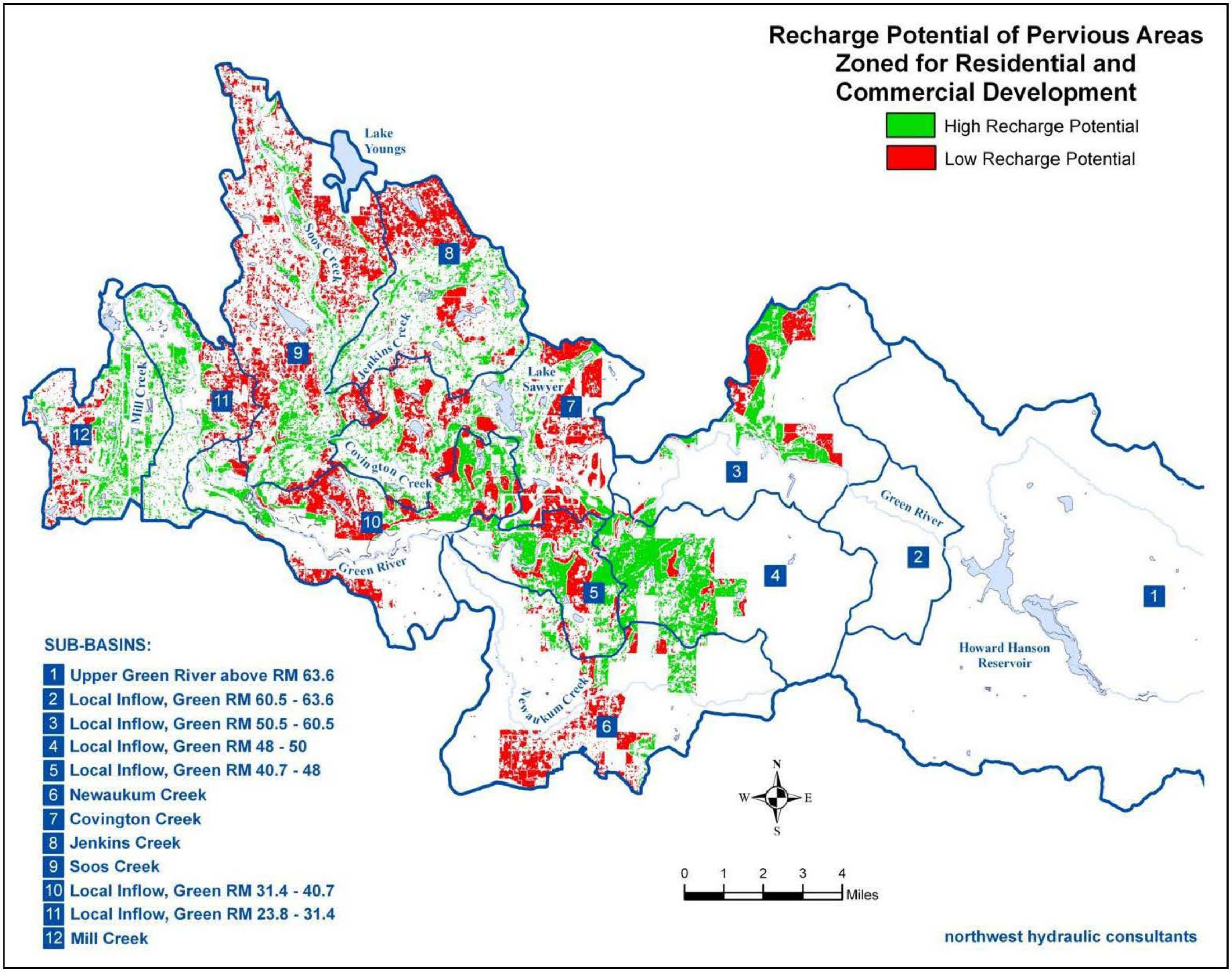


Figure 6.9. Recharge Potential of Pervious Lands Zoned for Development

7 Water Uses from Wells and Diversions

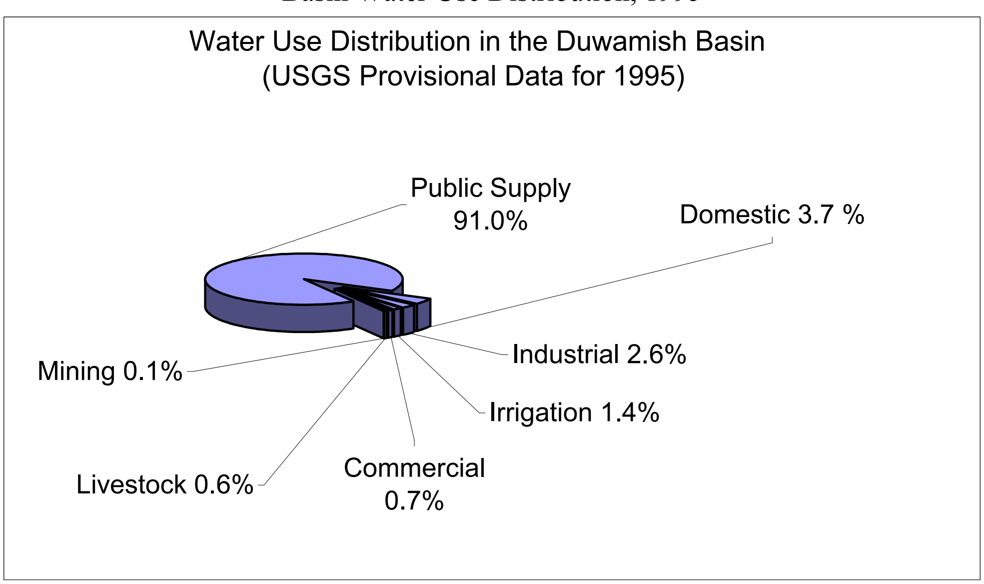
7.1 Overview

Several sources of data were used to identify existing wells and diversions which are currently in use. Primary data sources were State Department of Health records on public water supply systems and Department of Ecology records on water rights claims and certificates. Location information for public water supply wells was obtained from the King County Department of Natural Resources and Parks.

In this discussion, the terms “Group A” and “Group B” systems, and also permit exempt or “exempt wells” are frequently used and deserve explanation. Group A and Group B are identifiers used by the Department of Health to classify and regulate public water supply systems. Group A systems are public water supply systems with 15 or more service connections, plus some transitory and non-community systems[56]. Group B systems are public water supply systems with from 2 to 14 connections. The term “exempt well” is an identifier used by the Department of Ecology to identify relatively small wells which are allowed to withdraw groundwater without a water right permit issued by Ecology. Permit exempt wells are sometimes associated with small subdivision (up to six dwellings) water supplies which would in turn be regulated by the Department of Health as Group B public water supply systems. However, this is just one of the four classes of water permit exemptions which include: (1) stock watering; (2) watering of lawn or non-commercial garden areas not to exceed 1/2 acre in size; (3) domestic uses not exceeding 5,000 gallons a day; and (4) industrial purposes not exceeding 5,000 gallons per day.

Provisional water use data obtained from the US Geological Survey website show that water use in the Duwamish Basin, which includes the study area for this work, is dominated by public water use by systems with 15 or more connections. Figure 7.1 shows the water use breakdown for 1995, for which the USGS data shows the total basin population to be 319,760 persons, the irrigated land to be 600 acres, and the total average daily water use to be 60.1 million gallons per day (MGD). Public water supply plus self-supplied domestic use accounts for 95% of total water use.

Figure 7.1
Basin Water Use Distribution, 1995



[56] See Washington Administrative Code chapter 246-290-020 for a full definition of Group A & B systems.

Figure 7.2 shows the locations of active significant water sources in the study area, categorized by the amount of withdrawal. The figure shows the locations of all Group A and Group B water supply sources, plus irrigation, commercial, and mining sources with annual consumptive withdrawals greater than 10 MG. Figure 7.2 does not show the locations of any of the more than 3,000 single-connection exempt wells estimated from Section 7.2.2.1 to be active in the study area.

7.2 Current Uses

7.2.1 Public Water Supply Systems

Within the study area there are 31 Group A public water supply systems with 15 or more connections and 375 Group B public water supply systems with 2 to 14 connections. Table 7.1 provides population data for the public water supply systems which are active in the study area; the 12 largest Group A systems area listed individually. Figure 7.3 shows the service areas for the major water supply utilities in relation to the watershed basin areas being assessed.

Table 7.1
Public Water Supply Systems in Study Area

Public Water Supply System	Population from Year 2000 Census (or as noted)		
	Entire Service Area	Portion Within Study Area	
Covington Water District	42,845	41,459	97%
City of Auburn	49,349	34,459	70%
Soos Creek Water and Sewer District	54,945	26,969	49%
King County Water District 111	17,517	17,504	100%
Lakehaven Utility District	99,683	12,049	12%
City of Enumclaw	17,621	9,904	56%
City of Kent	55,002	8,079	15%
Cedar River Water and Sewer District	26,176	4,451	17%
Group B Systems (375 combined)*	3,471*	3,471	100%
City of Black Diamond	2,621*	2,545	97%
Other Group A Systems (24 combined)*	2,084	2,084	100%
City of Algona	2,691	467	17%
Muckleshoot Tribe	830	13	2%
Tacoma Water*	301,800*	0	0%
TOTAL		161,370	
* Populations served determined from Department of Health records			

Metered water withdrawals for calendar year 2000 were obtained by the Department of Ecology for all significant Group A public water supply sources in the study area. Data were not obtained on water transfers between utilities, such as for the Soos Creek Water and Sewer District which purchases water from Seattle Public Utilities, or the City of Algona, Water District 111, and Covington Water District which all purchase water from the City of Auburn. For systems such as the City of Kent, City of Auburn, and the City of Enumclaw, which operate independent water sources both within and outside of the study area limits, metered withdrawal data were obtained by Ecology only for those sources within the study area portion of the Green River basin.

.

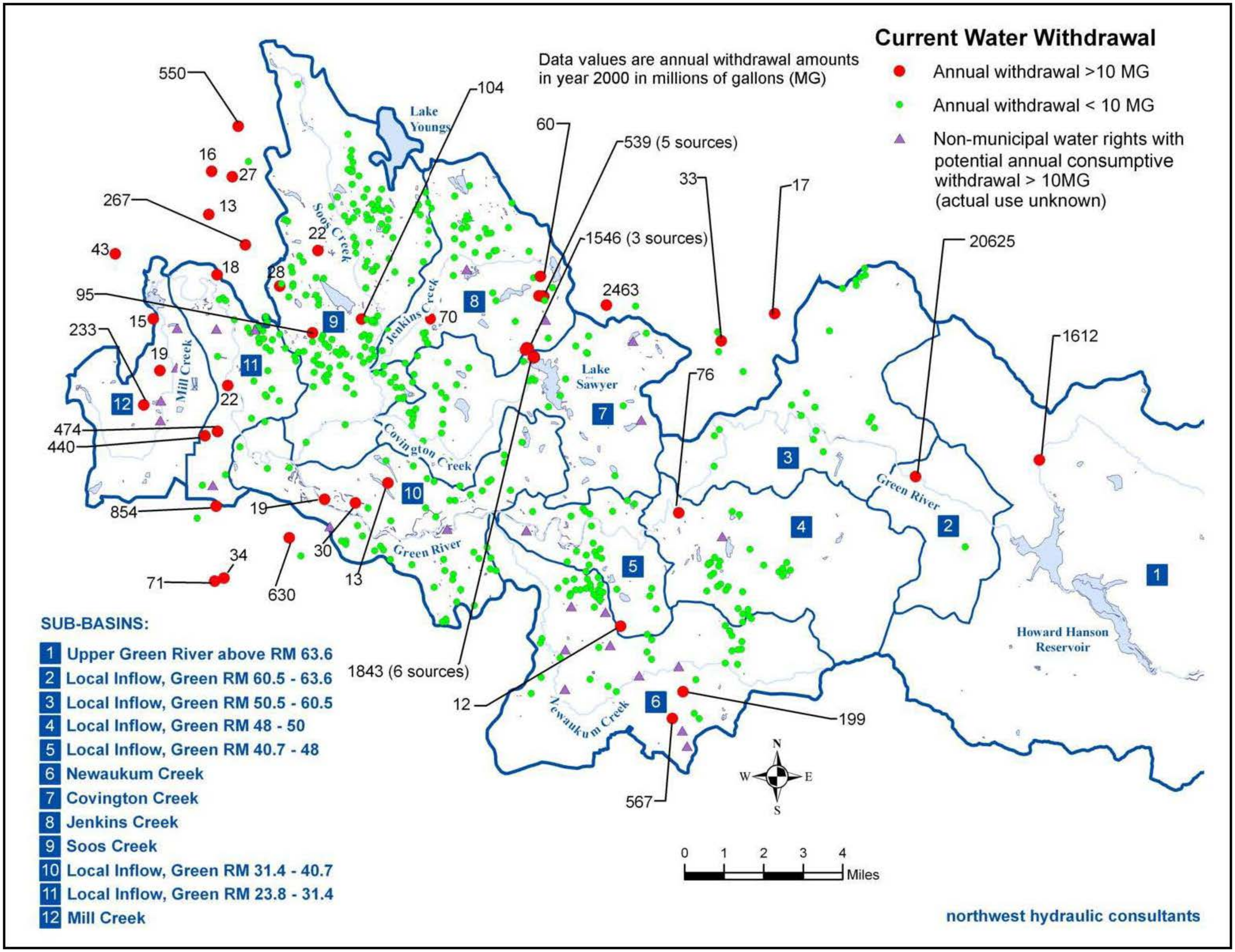


Figure 7.2. Current Water Withdrawals

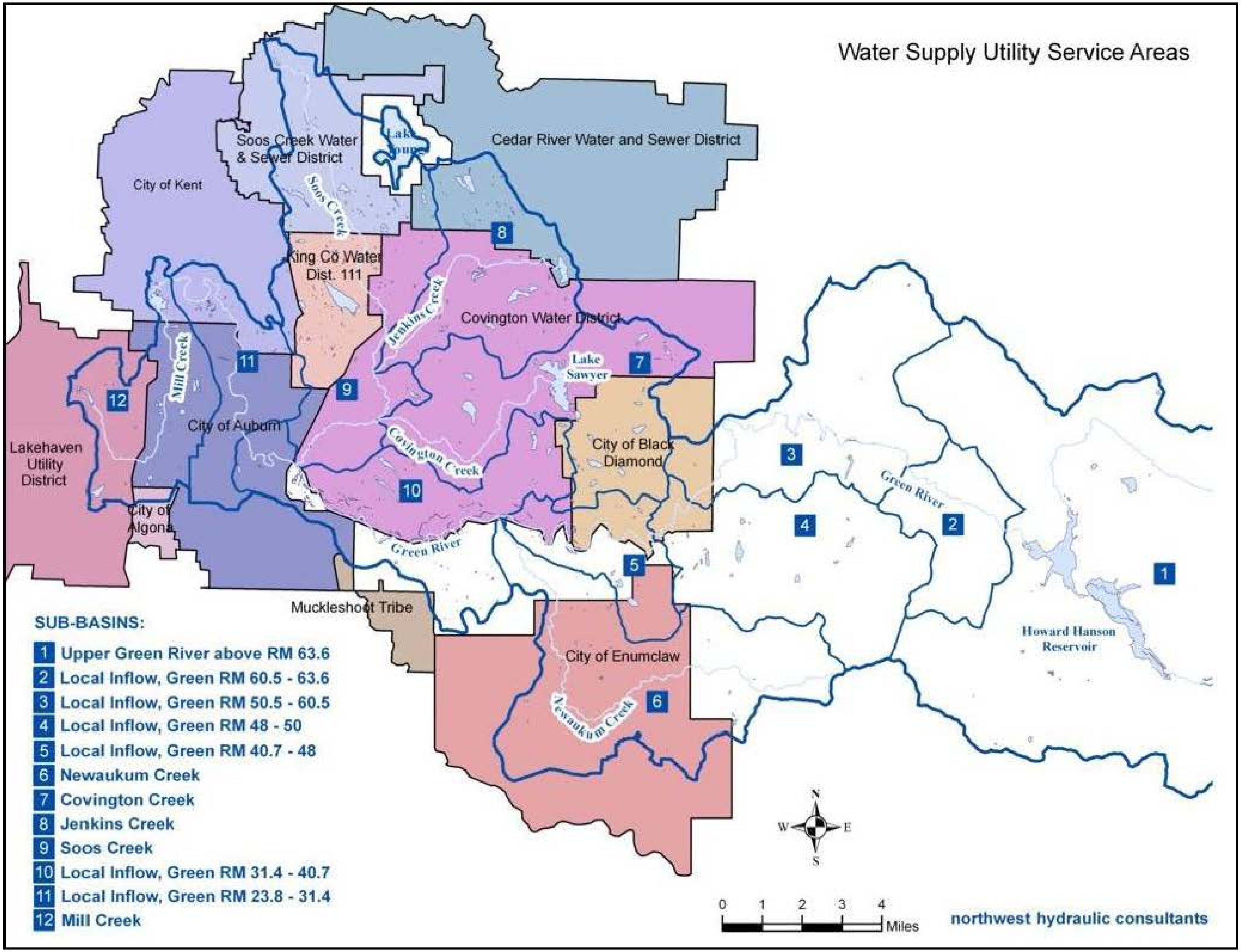


Figure 7.3. Water Utility Service Areas

Metered withdrawal records for the Group B systems and smaller Group A systems are not available. Estimates of the withdrawals were made with the assumption that each system is self-supplied with a source at the location of water use and, on average, withdraws water at the rate of 300 gallons per day per connection. Unit consumption rates for the Group A systems ranged from 237 (Soos Creek Water & Sewer) to more than 600 gallons per day per connection for systems with large industrial and commercial uses. A rate of 300 gallons per day is representative of single family residential consumption

The locations of all significant water withdrawals in the study area are shown in Figure 7.2. These include all study area sources for the Group A systems, the Group B systems, and other commercial and agricultural uses which could be confirmed with reasonable certainty. There are 51 confirmed water sources in and adjacent to the study area with annual withdrawals greater than 10 MG, plotted with a large circle. The locations of 424 confirmed water sources with annual withdrawals less than 10 MG are plotted with a small circle.

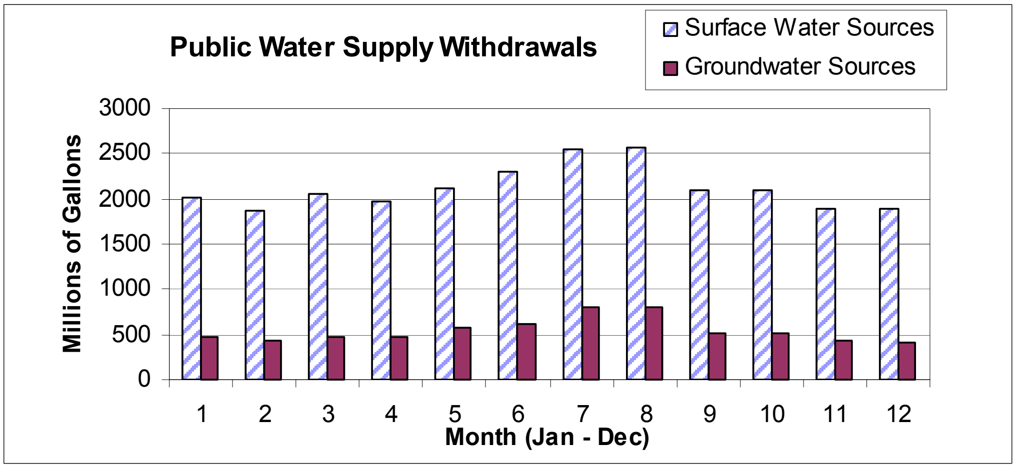
Figure 7.2 does not distinguish between sources for public water supply and for other uses because the overall withdrawals are so dominated by public water supply systems and because of incomplete data to describe the other types of withdrawal. Public water supply systems account for the largest 29 sources (all with annual withdrawals greater than 65 MG) and for one half of the sources with annual withdrawals between 10 and 65 MG. Commercial and industrial sources account for the remaining sources with annual withdrawals between 10 and 65 MG. Public water supply systems account for more than 95% of the sources categorized with less than 10 MG annual withdrawal. Other types of withdrawals, which include self-supplied irrigation, commercial, and domestic uses, are discussed later in this report.

Table 7.2 summarizes the annual public water system withdrawals by the sub-basin in which the source is located. Figure 7.4 shows the monthly distribution of public water system withdrawals for gauged sources, aggregated by surface and groundwater withdrawals. For purposes of Figure 7.4, Tacoma Water withdrawals from its intermittent-use north well field are aggregated with its primary surface diversion and are included in the bar representing surface diversions. Springs are included as surface water sources and spring withdrawals are included in the bar representing surface diversions.

Table 7.2
Public Water System Annual Withdrawals
(Including Group A and Group B Water Systems)

Sub-Basin		Year 2000 Extraction		Largest Purveyor (% of sub-basin withdrawals)
ID	Name	MG	equiv cfs	
1	Upper Green River above RM 63.6	1,612	6.8	Tacoma Water (100%)
2	Green River RM 60.5 – 63.6	20,625	87.4	Tacoma Water (100%)
3	Green River RM 50.0 – 60.5	23	0.1	Green R Gorge Resort (42%)
4	Green River RM 48 – 50	87	0.4	Black Diamond Water Dept (87%)
5	Green River RM 40.7 – 48	26	0.1	Y Bar S Water Co (45%)
6	Newaukum Creek	795	3.4	Enumclaw Water Dept (96%)
7	Covington Creek	1,859	7.9	Covington Water Dept (99%)
8	Jenkins Creek	2,180	9.2	Kent Water Dept (74%)
9	Soos Creek	283	1.2	KC Water Dist 111 (70%)
10	Green River RM 31.4 – 40.7	27	0.1	Diamond Springs Water (26%)
11	Green River RM 23.8 – 31.4	1,328	5.6	Auburn Water Division (97%)
12	Mill Creek	234	1.0	Auburn Water Division (100%)
1 – 12	Entire Study Area	29,080	123.2	Tacoma Water (76%)

Figure 7.4
Monthly Withdrawals by Reporting Public Water Supply Systems



The quantity of water supplied by major public water systems to each of the study sub-basins was estimated by apportioning each system's total supply to the respective sub-basins. Table 7.3 presents the total supply data, which are the Year 2000 Average Day Demand values obtained during preparation of the 2001 Central Puget Sound Regional Water Supply Outlook[57]. For Tacoma Water, which does not have a service district presence in the study area, the values shown are the Year 2000 metered withdrawals from the study area sources. The total supply values include non-revenue water due to system leakage and non-metered uses such as line flushing and fire fighting. Non-revenue water typically accounts for 5 to 15% of total supply for the systems in the study area. The total supply values mostly reflect the consumptive needs internal to each system and exclude wholesale water sales to other utilities, with the exception of data for Auburn which was later found to include 1.76 MGD in wholesale water.

Table 7.3
Major Water Utility Total Supplied Water
(Data give water to entire service area not limited to study boundaries, from all sources of supply)

Utility	Year 2000 Average Day Demand	
	MGD	equiv cfs
Covington Water District	4.1	6.3
City of Auburn	8.2	12.6
Soos Creek Water and Sewer	4.5	7.0
King County Water District 111	1.7	2.6
Lakehaven Utility District	10.5	16.3
City of Enumclaw	3.3	5.1
City of Kent	8.6	13.3
Cedar River Water and Sewer	1.9	2.9
City of Black Diamond	0.2	0.3
City of Algona	0.4	0.6
Tacoma Water*	60.9	94.3

* For Tacoma Water only, values are limited to extraction amounts from WRIA 9 sources.

[57] Average Day Demand data were obtained from RW Beck, co-author of the Water Supply Outlook. The data for some utilities are suspected to be high demands, higher than actual. The demand values are internal to each service area and, except for the City of Auburn, do not include wholesale water sold to other purveyors.

Apportioning of the major systems' total water supply to the study sub-basins was made with a GIS analysis of year 2000 census data and associated Traffic Analysis Zone (TAZ) data[58]. For each utility service area, the numbers of residences, multi-family residences, and employees were determined for the entire service area and for each of the sub-basins being assessed. These base numbers were converted to water use Equivalent Residential Units (ERU) based on approximate unit consumption amounts,[59] converted to ERUs as shown below.

Single-family residential	300 gallons per household per day	(1 residence per ERU)
Multifamily residential	50 gallons per household per day	(6 households per ERU)
Non-residential	45 gallons per employee per day	(6.66 employees per ERU)

Water supplied to each sub-basin, by each major utility named in Table 7.1, was computed as the product of each utility's total supply to all areas and the percentage of total ERUs within each sub-basin. For the smaller public water supply systems not identified in Table 7.1, water uses were assumed to occur within the same sub-basin as the water supply source.

Table 7.4 summarizes the public water supply currently provided in each of the sub-basin areas.

Table 7.4
Public Water System Delivered Water Supply
(Including Group A and Group B Water Systems)

Sub-Basin		Year 2000 Delivered Water Supply		
ID	Name	MG	equiv MGD	Equiv cfs
1	Upper Green River above RM 63.6	0	0.0	0.0
2	Green River RM 60.5 - 63.6	0	0.0	0.0
3	Green River RM 50.0 - 60.5	24	0.1	0.1
4	Green River RM 48 – 50	12	0.0	0.0
5	Green River RM 40.7 – 48	62	0.2	0.3
6	Newaukum Creek	455	1.2	1.9
7	Covington Creek	421	1.2	1.8
8	Jenkins Creek	866	2.4	3.7
9	Soos Creek	1,972	5.4	8.4
10	Green River RM 31.4 - 40.7	499	1.4	2.1
11	Green River RM 23.8 - 31.4	1,371	3.8	5.8
12	Mill Creek	1,086	3.0	4.6
1 - 12	Entire Study Area	6,769	18.5	28.7

58 TAZ data with employment information were obtained from the Puget Sound Regional Council subject to a confidentiality agreement.

59 Water use factors were estimated with consideration of values presented in the Water Supply Outlook and guildelines in the Washington Department of Health August 2001 Water System Design Manual. Values presented in the Water Supply Outlook were: single-family residential at 205 gallons per household per day, multifamily residential at 25 gallons per household per day, and non-residential at 42 gallons per employee per day. Current usage is expected to be greater than the Outlook projections which include conservation assumptions.

7.2.2 Withdrawals not for Public Water Supply

The USGS estimates of water use in the Duwamish Basin (see Figure 7.1) show that about 91% of total water use in 1995 was for Group A System public water use. Self-supplied withdrawals for Group B and smaller domestic systems, commercial, industrial, irrigation, livestock, and mining uses account for the remaining 9%. Data to confirm the locations of and current withdrawals from sources not for public water supply were not available in a compiled format and were estimated by other methods.

The data and information sources identified below were used to estimate sources and withdrawals for non-public water supply systems.

- Water withdrawal data from 1986 for the lower portion of the study area, published in USGS Water-Resources Investigations Report 92-4098, "Occurrence and Quality of Ground Water in Southwestern King County, Washington."

- Department of Ecology's Water Rights Tracking System (WRTS) which is a database of water rights claims, certificates, and applications statewide. Department of Ecology staff assisted with the processing, screening, and interpretation of the WRTS data.

- Department of Ecology's databases of water well reports. Department of Ecology staff assisted with the processing, screening, and interpretation of the water well data.

- Personal communication with Tom Beavers, the watershed steward for the Enumclaw Plateau.

Based on the USGS estimates, self-supplied domestic use accounts for about one half of all non-public water supply uses in the Duwamish Basin. Irrigation, industrial, commercial, mining, and livestock uses account for the remainder.

7.2.2.1 Self-Supplied Domestic Use

Self-supplied domestic uses are generally associated with permit exempt wells for which no water right paper work is required by the Department of Ecology. However, exempt wells are tracked by the Department of Ecology via well construction records and those exempt wells with more than one service connection are regulated by the Department of Health as Group B water supply systems. This section presents an evaluation of withdrawals and consumption from self-supplied domestic use for single-connection systems.

For the purposes of the current study, the Department of Ecology evaluated the number of exempt wells in each sub-basin and estimated the withdrawals from active exempt wells not already counted as Group B public water supply systems. Water use from the Group B systems is already included in the public water supply consumption numbers presented in Section 7.2.

Ecology has two databases associated with water wells. The first is the Notice of Intent to Construct a Water Well (NIT, started in 1993) and the second is the Water Well Reports. The NIT database has data on the use of the well, either single domestic, group domestic, or other. The Water Well Reports database started in 1972, but was only populated with water well reports systematically since 1975. In general it took several years for the well drilling community to do water well reports and submit them. In both databases, the well locational data is, at best, ¼, ¼, ¼, of the Section, within a Township and Range.

The Water Well Report database was mined for all records that fall within WRIA 9. Then, Ecology correlated those records (post 1993) with a notice of intent from the Notice of Intent to Construct a Water Well. Those records that had both a water well report and a notice of intent were reviewed to exclude records for group domestic use leaving the single domestic water wells.

The resulting records of water wells were then mapped in GIS to the ¼ of the ¼ of the ¼, of the Section within a Township and Range. The map of water wells was then overlaid with the sub-basin shape files to determine the number of water wells in each sub basin. In many cases when detailed location information was lacking or incomplete, the wells were mapped to the center of the Section.

To estimate the water used by the single connection domestic (exempt) wells on an annual basis, a water duty of 120 gallons per day average was multiplied by the number of wells and then by 345 to calculate the indoor water used in 345 non-peak days. It is assumed that water is also used outside for 20 days a year during the months of July, August, and September. A water duty of 120 gpd multiplied by an Ecology-estimated peaking factor of 2.8 is equal to 336 gpd. The 336 gpd was multiplied by 20 days and added to the indoor water use to arrive at annual water use for each well. This annual water use was multiplied by the number of permit exempt wells in the basin to estimate total basin water use by permit exempt wells.

Table 7.5 summarizes the results of the exempt well analysis

Table 7.5
Estimated Self-Supplied Domestic Use from Exempt Wells

Sub-Basin		# of Single-Connection Wells	Exempt Well Withdrawal	
ID	Name		Annual MG	equiv cfs
1	Upper Green River above RM 63.6	6	0.3	0.00
2	Green River RM 60.5 - 63.6	0	0.0	0
3	Green River RM 50.0 - 60.5	229	11.0	0.05
4	Green River RM 48 - 50	203	9.8	0.04
5	Green River RM 40.7 - 48	215	10.3	0.04
6	Newaukum Creek	381	18.3	0.08
7	Covington Creek	287	13.8	0.06
8	Jenkins Creek	384	18.5	0.08
9	Soos Creek	682	32.8	0.14
10	Green River RM 31.4 - 40.7	457	22.0	0.09
11	Green River RM 23.8 - 31.4	110	5.3	0.02
12	Mill Creek	84	4.0	0.04
1 – 12	Entire Study Area	3,038	146	0.62

7.2.2.2 Irrigation, Commercial, and Other Consumptive Uses

The Department of Ecology water rights records provide a comprehensive dataset of water supply sources. However, the data are in the form of unverified claims and certificates of potential legal use and many of those claimed and certificated sources may presently be inactive or underutilized. The water rights records are insufficient to identify active sources and current water usage.

Confirmed water use data from year 1986 from wells in the lower portion of the study area is available from the 1995 USGS Water-Resources Investigations Report 92-4098. That study identifies source locations and annual withdrawals in 1986 for wells used for irrigation and commercial/industrial uses. The USGS study area encompasses the Soos, Jenkins, Covington, and Mill Creek drainage basins plus areas of local inflow to the Green River below the confluence of Soos Creek and the Green River. The USGS study area did not include either the Newaukum Creek basin or the area of Icy Creek and Black Diamond Springs, and the study did not address surface water withdrawals.

The water use data in the USGS report is felt to provide a reliable source of groundwater withdrawal data that is sufficiently recent to characterize irrigation and commercial uses in the lower portion of the study area. Table 7.6 summarizes the USGS data for the wells located in the sub-basins established in the current work. Commercial water withdrawals in the study area from the USGS data totaled only 1.1 MG from two wells (one each in sub-basins 8 and 11) and are insignificant to basin-scale results. All of the irrigation and commercial water sources from the USGS study are included in the Figure 7.2 plot of the current water withdrawal locations and amounts.

Table 7.6
Irrigation and Commercial Water Withdrawals from USGS-Identified Wells in 1986

Sub-Basin		Non-PWS Withdrawal		Major Use
ID	Name	MG	equiv cfs	
1-5	Green River above RM 40.7	n/a	-	-
6	Newaukum Creek	n/a	-	-
7	Covington Creek	0.3	0.0	Irrigation (2 wells)
8	Jenkins Creek	60.8	0.3	Irrigation (1 well)
9	Soos Creek	32.3	0.1	Irrigation (5 wells)
10	Green River RM 31.4 - 40.7	61.3	0.3	Irrigation (4 wells)
11	Green River RM 23.8 - 31.4	46.0	0.2	Irrigation (6 wells)
12	Mill Creek	18.9	0.1	Irrigation (2 wells)
1 - 12	Study Area covered by USGS	220	0.9	

Assessment of water uses from surface water sources, and water uses outside the USGS study area required use and interpretation of Ecology's water rights records. Ecology staff assisted greatly with this work.

A preliminary screening of water rights certificates in the study area was performed by the Department of Ecology to identify those records representing large, active, consumptive, sources other than for the Group A and B public water supply systems. The screening excluded primarily non-consumptive withdrawals such as for fish hatchery use. The screening was performed by Ecology staff familiar with the study area, and yielded a list of 96 potentially significant "other" water withdrawals. However, the Ecology staff cautioned that the screening process had not confirmed which sources were (and were not) active and was therefore not reliable as a list of active uses.

The preliminary Ecology list was further screened to remove groundwater sources in the lower basin that appeared to duplicate the more reliable information from the USGS study discussed above. This further screening was highly subjective because of poor locational information and a lack of other information to relate the USGS and Ecology data sets.

Table 7.7 below presents a summary of the information derived from the water use certificate data for non-public water supply sources. The estimated annual water use for each of the sources in the Ecology list was estimated to be the lesser of: (1) the annual withdrawal listed by the certificate; or (2) in the case of irrigation uses, an annual amount of 0.3 MG per acre (about 11 inches depth) representing a high estimate of annual consumptive use for irrigated lands in the study area. The locations of significant "other" sources with an estimated annual withdraw of more than 10 MG are shown with a unique (triangle) symbol on Figure 7.2. It should be noted that the actual use associated with these certificates has not been confirmed and that the larger uses are potentially non-consumptive.

Table 7.7
Potential Other Non-Public Water Supply Significant Water Withdrawals and Uses
Estimates from Ecology Water Rights Certificates

Sub-Basin		Estimated Potential Use		Sources (See notes below for additional detail)
ID	Name	Annual MG	equiv cfs	
1	Upper Green R above RM 63.6	-		
2	Green River RM 60.5 - 63.6	-		
3	Green River RM 50.0 - 60.5	7	0.0	1 well
4	Green River RM 48 – 50	10	0.0	1 source - Lake Isabel
5	Green River RM 40.7 – 48	> 40	> 0.2	6 surface water sources
6	Newaukum Creek	70	0.3	21 sources, sw & gw.
7	Covington Creek	> 744	> 3.2	2 wells, 2 lakes
8	Jenkins Creek	104	0.4	3 wells
9	Soos Creek	13	0.1	3 sources, sw & gw
10	Green River RM 31.4 - 40.7	64	0.3	8 sources, sw & gw
11	Green River RM 23.8 - 31.4	364	1.5	20 sources, sw & gw
12	Mill Creek	44	0.2	4 sources - all Mill Creek
1 - 12	Entire Study Area	> 1,460	> 6.2	

Notes

- Sub-basin 5 estimate does not include commercial use withdrawals from Green River by Smith Brothers.
- Sub-basin 6 (Newaukum Creek Basin) water use estimate is based on information from the basin watershed steward that less than 1% of the basin is irrigated, and that the predominant agricultural use is cattle and dairy operations for approximately 2,500 head of cattle. Annual water use is estimated at 0.3 MG per acre for 173 irrigated acres (1% of basin) plus 25 gpd for 2,500 cows. This estimated water use is thought to be more accurate than one based on the water rights certificates which suggest more than 250 MG annual use with irrigation of more than 1,000 acres.
- Sub-basin 7 estimate dominated by 744 MG potential annual withdrawal from Ravensdale Lake by Burlington Northern. Additional (not quantified) mining use withdrawal from Mud Lake by Pacific Coast Coal.
- Sub-basin 8 estimate dominated by 92 MG potential annual withdrawal by Black River Quarry.
- Sub-basin 11 estimate dominated by 290 MG potential annual withdrawal by Miles Co well.

7.3 Authorized Additional Future Uses

Future water demands and sources of supply are evaluated at length in the July 2001 Central Puget Sound Regional Water Supply Outlook. Municipal and domestic water demands are expected to increase in response to a growing population and are estimated in the Outlook based on long-term population, household, and employment forecasts. Non-municipal demands are expected to remain essentially at the same level as current conditions. The Outlook provides demand estimates and various proposals for meeting future municipal demands, including the full use of existing (authorized) water rights, various new water development projects, interbasin transfers, and conservation. The discussion here is limited to existing municipal water rights which are currently under-utilized. Existing water rights are generally insufficient to meet future demands, but discussion and resolution of that larger issue is beyond the scope of this study.

For the present work it is assumed that future growth in water extraction will occur exclusively by the large municipal purveyors already active in the study basins. No significant change is expected to the current levels of self-supplied commercial, agricultural, and other non-municipal water use. The numbers of active exempt wells for domestic supply and smaller public water systems are also assumed to continue unchanged into the future. This same assumption was made in the analysis for the Water Supply Outlook, speculating that there might be an approximate balance between new non-public water supply wells and those which are abandoned after connecting to the larger municipal systems.

The assumptions on active exempt wells are believed to be reasonable in the urban growth areas which are served by public water supply systems, but may under-estimate the future effects of exempt wells in undeveloped areas which are zoned for low-density residential development. However, exempt wells now account for less than 0.3% of total delivered water supply in the study basins and the total effect of new exempt wells in rural areas is likely to be similarly low in comparison with other withdrawals and diversions.

Generally, Ecology is unlikely to approve new water rights applications for consumptive, year around, use of surface or ground water in the study basin. Water right decisions in the study basin are guided, in part, by chapter 173-509 WAC. The WAC is related to instream resource protection and provides little opportunity for new consumptive uses of a year around nature. Most of the tributaries to the Green River are closed to new consumptive uses. The Green River also has established instream flows. Any water rights issued from the Green River would be subject to interruption during those time periods instream flows are not met. In some cases, new water rights may be approved if the project proponent provides mitigation for instream flow impacts. The opportunities for that are also limited. The consequence is that additional extraction in the study area basins will, for the foreseeable future, be limited to exercising inchoate water rights. Inchoate rights are the rights above the current water use and less than or up to the available certificated amount.

Table 7.8 summarizes the water rights and current use data for each of the major public water supply systems which are active in the study area. The data are as reported in the Water Supply Outlook and, with the exception of Tacoma Water, represent each utility's total service area and sources not limited to the study areas for the current work. The Tacoma Water data are limited to withdrawals from the Green River basin. An assessment of source-specific water rights for each major utility, and allocation of available unused amounts to the study sub-basins, could not be determined from the data in the Water Supply Outlook and could not be independently accomplished with the resources available for this study.

The Water Rights Qa and Qi data in Table 7.8 are, respectively, the annual and instantaneous maximum rates of withdrawal available to each utility under existing water rights certificates issued by the Department of Ecology. The timing of Qi relative to Qa is a function of seasonal or sudden (i.e. firefighting) demand and the storage volumes available to each utility. If sufficient storage is available and there are no other constraints, each utility can potentially provide an Average Day Demand water supply equal to its water right Qa amount. Where other known constraints exist, the available Average Day Supply is less than the water right Qa amount. Because of seasonal demand fluctuations, some utilities may already be withdrawing at the maximum Qi amount during summer peak-demand months and have significant reserve capacity to produce additional water only during the winter months.

Table 7.8
Municipal Utilities' Available (Unused) Water Supplies

Water Supply Utility	Water Rights Qa / Qi MGD	Primary Constraint	Available Avg Day Supply MGD	Year 2000 Avg Day Demand MGD	Unused Avail Avg Day Supply	
					MGD	equiv cfs
Cedar R. Water & Sewer	0.05 / 0.17	water rights	0.05	1.86	0	-
City of Algona	purchased water		-	0.36	0	-
City of Auburn	20.8 / 27.0	instream flow	18.28	8.15	10.13	15.7
City of Black Diamond	0.49 / 5.24	water rights	0.49	0.21	0.28	0.43
City of Enumclaw	3.43 / 4.20	water rights	3.43	3.28	0.15	0.23
City of Kent	25.9 / 40.3	aquifer yield	17.0	8.60	8.40	13.0
Covington Water District	5.44 / 7.92	water rights	5.44	4.07	1.37	2.1
King County WD 111	1.97 / 2.77	water rights	1.97	1.66	0.31	0.49
Lakehaven Utility District	18.0 / 42.8	aquifer yield	10.1	10.51	0	-
Soos Ck Water & Sewer	purchased water		-	4.49	0	-
Tacoma Water	n/a	instream flow	137.7	60.92	76.78	118.8

Authorized additional future uses are the unused portion of the available Average Day Supply, computed as the difference between the available Average Day Supply and the current (year 2000) Average Day Demand. Negative values computed for several of the districts indicate that some or all of the water supply for those utilities is currently obtained through wholesale purchases from other purveyors.

The largest authorized additional future use, nearly 120 cfs, is associated with implementation of Tacoma Water's second diversion water right. The impacts of those future withdrawals on Green River flows have been assessed and the resulting post-withdrawal streamflow statistics are included in Section 3.2. The impacts of the other authorized additional uses, including nearly 16 cfs by the City of Auburn, and 13 cfs by the City of Kent, are unknown at this time. Additional work would be required to identify the specific sources for that additional water, and an assessment made of the timing of additional withdrawals and identification of the surface water systems (streams, rivers, lakes, wetlands) most likely to be affected.

8 Interbasin Transfers and Adjustments

8.1 Hydraulic Continuity of Groundwater and Surface Water

A reconnaissance level analysis was made of 420 active wells in the study area to assess whether groundwater withdrawals would impact streamflows in the basin with the well (e.g., the source locations as plotted in Figure 7.2) or in separate, hydraulically-connected, sub-basins. For this study it was assumed that groundwater withdrawals normally result in reduced streamflow; the purpose of the continuity assessment was to assess where those reductions would occur. Withdrawals from surface water sources are assumed to only impact streamflows in the sub-basin where the diversion occurs.

When a well begins pumping, localized hydraulic conditions change. The head (water level) drops in the well, increasing the groundwater gradient—and therefore flow—to the well. Initially, the pumped water is captured from nearby areas in the aquifer. As pumping continues, however, water may be captured from areas that lie increasingly farther from the well. The size of this radial "zone of influence" depends on several factors, including the well's pumping rate and the aquifer properties (transmissivity, confinement, etc.) In areas where surface water and groundwater are hydraulically connected, impacts to lakes, streams, or wetlands increase with proximity to the pumping well. Well withdrawals may affect flow in these features as they capture surface water from them directly or as they intercept groundwater flow to them. Under certain conditions, the pumping wells may intercept groundwater flow to marine waters, changing the position of the freshwater-saltwater interface.

Several steps are required to quantitatively predict the effects of pumping on surface water bodies. First, hydrogeologic conditions must be characterized using data collected in the field. Second, a conceptual model of the surface water-groundwater system must be developed. Finally, a mathematical model must be constructed. Mathematical models vary widely in their complexity, ranging from relatively simple assumptions to complex, distributed-parameter, numerical solutions. Modeling approaches are typically driven by budgets, available data, time, and project goals.

For this project, qualitative assessments were made to estimate the potential effects of pumping from 420 wells that were divided into two groups: (1) wells that produce more than 50 MG annually and (2) wells that produce less than 50 MG. The assessment of wells in these two groups resulted in estimates of the impacts of withdrawals from wells on surface water in the sub-basins.

For the first group, which consisted of 17 Group A public water supply wells, information available from hydrogeologic studies was reviewed and professional judgment was used to assess impacts. The following sub-basin scale information was reviewed for estimating allocations of impact to sub-basins:

- The locations of wells relative to surface water features in the sub-basin
- The aquifers tapped by the wells
- Groundwater flow directions
- Surface water / groundwater relationships, where known

A simpler qualitative approach was used for the second group, which included 31 Group A and 372 Group B public water supply wells. This approach involved calculating the elevation of each well bottom and comparing it to the elevation at the outlet of the well's sub-basin. If the well bottom was higher than

the outlet, pumping was assumed to affect streamflow within the sub-basin. If the well bottom was lower, it was compared to outlets of downgradient sub-basins to determine potential effects on them.[60]
Table 8.1 summarizes the results of this assessment, and allocates well withdrawals to specific basins. To illustrate how these results are applied, the table shows that Enumclaw Water Department withdrawals from well # 23600_04 in the Newaukum Creek basin would have surface water impacts in Newaukum Creek and also in WRIA 10, which is the White River basin. The total annual withdrawal of 199 MG from this well would be allocated as an annual surface water reduction of 139 MG (computed as 70% of 199) from Newaukum Creek and 60 MG reduction from surface water in WRIA 10.

Table 8.1 shows that each of the 17 public water supply wells producing more than 50 MG annually is estimated to have surface water impacts in the basin where the well is located, and also in at least one other basin. The results indicate that from 5 to 50 percent of the surface water impact for each well occurs in downgradient or adjacent basins. In contrast, 388 of the 403 smaller-capacity wells were estimated to have impacts exclusively in the basin where the well is located, and only 15 wells with surface water impacts in downgradient basins. Note that these qualitative estimates are based on professional judgment; actual impacts may differ substantially. Refining these estimates would require detailed characterization and modeling, which was beyond the scope of this project.

Table 8.2 translates these hydraulic continuity results into net change adjustments that can be added to the source-based public water supply withdrawals in Table 7.2 to estimate potential surface water impacts in each sub-basin. Using the Covington Creek sub-basin for illustration, Table 7.2 shows a total withdrawal of 1,859 MG for public water supply in year 2000, and Table 8.2 shows an adjustment of -108 MG. After adjustment for continuity effects, the water supply withdrawals in year 2000 are thereby estimated to have reduced streamflows in Covington Creek by approximately 1,751 MG (7.4 cfs). This streamflow adjustment is approximate because it does not address return flows to the stream from processes which include septic systems, car washing, and over-watering of lawns. It should be noted also that these adjustments do not account for impacts from wells located outside the study area portion of WRIA 9.

[60] Pumping from a capture point below the basin outlet does not preclude the possibility of surface water impacts within the basin where the pumping occurs. The simpler qualitative approach described above was felt to be appropriate for the current study but may not be applicable in other contexts.

Table 8.1
Wells with Potential Surface Water Impacts in Downgradient and Adjacent Basins

Source Location Basin		System Name	PWSID	Annual MG	Est. % Impact In Basin	Estimated Impact Outside Basin	
ID	Name					%	Basin
***GROUP 1**: Sources with Annual Withdrawal > 50 MG; some non-coincident impacts for all PWS wells assessed*							
6	Newaukum Creek	Enumclaw Water Dept	23600_04	199	70	30	WRIA 10
7	Covington Creek	Covington Water District	41650_13	938	80	20	Jenkins Ck
7	Covington Creek	Covington Water District	41650_10	303	80	20	Jenkins Ck
7	Covington Creek	Covington Water District	41650_12	218	80	20	Jenkins Ck
7	Covington Creek	Covington Water District	41650_09	164	80	20	Jenkins Ck
7	Covington Creek	Covington Water District	41650_07	149	80	20	Jenkins Ck
7	Covington Creek	Covington Water District	41650_01	70	80	20	Jenkins Ck
8	Jenkins Creek	Kent Water Dept	38150_13	508	50	50	Covington Ck
8	Jenkins Creek	Covington Water District	41650_04	269	70	30	WRIA 8
8	Jenkins Creek	Covington Water District	41650_15	107	70	30	WRIA 8
8	Jenkins Creek	Covington Water District	41650_03	72	70	30	WRIA 8
8	Jenkins Creek	Kent Water Dept	38150_08	70	65	25 10	Soos Creek Covington Ck
8	Jenkins Creek	Covington Water District	41650_11	52	70	30	WRIA 8
9	Soos Creek	K.C. Water Dist 111	41900_08	104	50	50	below study limit
9	Soos Creek	K.C. Water Dist 111	41900_07	95	50	50	below study limit
11	Green 23.8-31.4	Auburn Water Division	03350_11	439	75	15 5 5	Mill WRIA 10 below study limit
11	Green 23.8-31.4	Auburn Water Division	03350_04	380	75	15 5 5	Mill WRIA 10 below study limit
***GROUP 2**: Sources with Annual Withdrawal < 50 MG; non-coincident impacts in 15 of 403 sources screened*							
4	Green 48-50	Cunningham, M.	52236	0.3	0	100	below study limit
4	Green 48-50	Strawberry	04552	0.2	0	100	Green 31.4-40.7
5	Green 40.7-48	Flaming Geyser # 3	59314	0.7	0	100	Green 31.4-40.7
8	Jenkins Creek	Underfer, L.	90215	0.8	0	100	Soos Creek
8	Jenkins Creek	Young, G.	99430	0.3	0	100	below study limit
8	Jenkins Creek	Wallis	38301	0.2	0	100	Soos Creek
9	Soos Creek	Lundberg/Dunphy	02234	0.4	0	100	Green 23.8-31.4
9	Soos Creek	Person & Person	43055	0.4	0	100	below study limit
9	Soos Creek	Green R Hatchery	29489	0.3	0	100	below study limit
9	Soos Creek	Hilling	22171	0.3	0	100	below study limit
9	Soos Creek	Kohlmeier/Western	42947	0.2	0	100	below study limit
10	Green 31.4-40.7	O'Well	03621	0.2	0	100	below study limit
10	Green 31.4-40.7	Sargeant's Addition	76350	0.2	0	100	below study limit
10	Green 31.4-40.7	Neely Mansion	04895	0.1	0	100	below study limit
11	Green 23.8-31.4	M. C. Public	01233	0.3	0	100	below study limit

Notes: PWSID= public water system identification.

Table 8.2
Well Withdrawal Adjustments for Non-Coincident Surface Water Impacts

Sub-Basin		Adjustment Amount	
ID	Name	Annual MG	equiv cfs
1	Upper Green R above RM 63.6	n/a	-
2	Green River RM 60.5 - 63.6	n/a	-
3	Green River RM 50.0 - 60.5	n/a	-
4	Green River RM 48 – 50	-1	0.0
5	Green River RM 40.7 – 48	-1	0.0
6	Newaukum Creek	-60	-0.3
7	Covington Creek	-108	-0.5
8	Jenkins Creek	-62	-0.3
9	Soos Creek	-82	-0.3
10	Green River RM 31.4 - 40.7	0	0.0
11	Green River RM 23.8 - 31.4	-205	-0.9
12	Mill Creek	123	0.5
1 - 12	Entire Study Area	-396	-1.7

Note: Adjustments to be added to source-based withdrawals in Table 7.2

8.2 Interbasin Transfers of Public Water Supplies

Interbasin transfers of water of public water supply occur when water is piped from a well or diversion in one basin and exported for use in a different basin. Water transfers are common in the study areas. For example, the Soos Creek Water and Sewer District relies entirely on water purchased from Seattle Public Utilities and which originates in the Cedar River watershed. The City of Kent operates water sources in both the Cedar and Green River watersheds, and the Cities of Auburn and Enumclaw each operate water sources in both the White and Green River watersheds. All of the major water supply utilities shown on Figure 7.3 have service areas which cross the sub-basin limits established for the current work.

Annualized interbasin transfers of public water supplies to and from each of the study sub-basins were estimated by taking the difference between municipal water extraction (Table 7.2) and the water supplied (Table 7.4) in each sub-basin area. The inferred import and export amounts are presented in Table 8.3.

Table 8.3
Public Water System Inferred Imports and Exports
(Difference between Table 7.2 source withdrawal and Table 7.4 delivered supply)

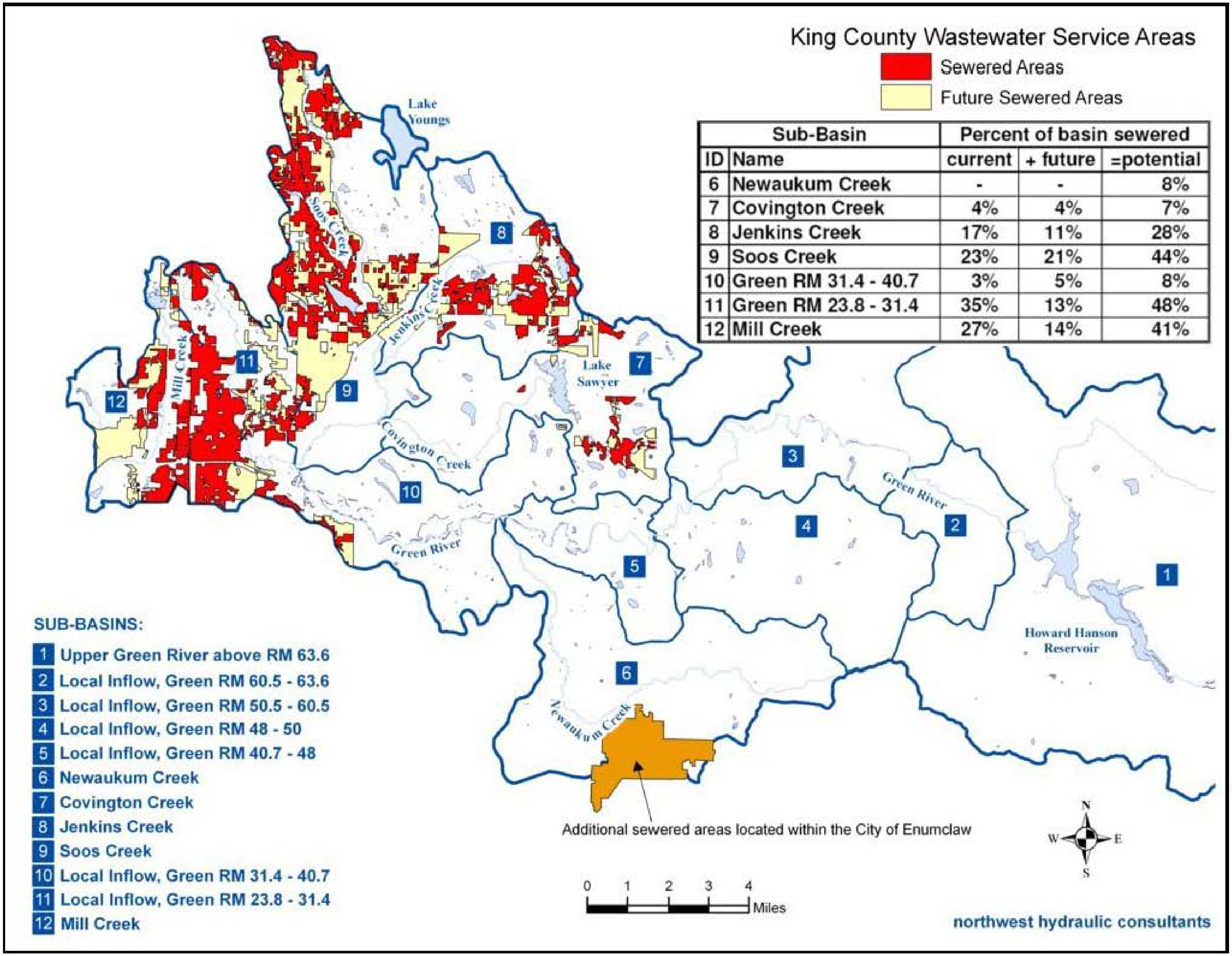
Sub-Basin		Year 2000 Water Import (+) or Export (-)*		
ID	Name	Annual MG	equiv MGD	Equiv cfs
1	Upper Green River above RM 63.6	-1,612	-4.4	-6.8
2	Green River RM 60.5 - 63.6	-20,625	-56.5	-87.4
3	Green River RM 50.0 - 60.5	1	0.0	0.0
4	Green River RM 48 – 50	-75	-0.2	-0.3
5	Green River RM 40.7 – 48	36	0.1	0.2
6	Newaukum Creek	-340	-0.9	-1.4
7	Covington Creek	-1,438	-3.9	-6.1
8	Jenkins Creek	-1,314	-3.6	-5.6
9	Soos Creek	1,689	4.6	7.2
10	Green River RM 31.4 - 40.7	472	1.3	2.0
11	Green River RM 23.8 - 31.4	43	0.1	0.2
12	Mill Creek	852	2.3	3.6
1 - 12	Entire Study Area	-22,311	-61.1	-94.6

* Positive numbers indicate that water supply is met with imports from other sub-basins; negative values indicate that water is being exported.

8.3 Wastewater Exports

King County operates a regional wastewater system that provides treatment for about 1.4 million people in the Puget Sound region. Figure 8.1 shows the extent of the wastewater collection system in the study area; water from this area is treated at the County's South Treatment Plant in Renton and discharged to a deepwater outfall in Puget Sound. The city of Enumclaw operates an independent wastewater system within the city limits, and discharges treated water to the White River. The King County and Enumclaw wastewater systems both result in water exports from the study basins.

Wastewater flows are a combination of base sewage plus additional infiltration and inflow often described as "I and I" or I/I. These components are discussed below.



Sub-Basin		Percent of basin sewered		
ID	Name	current	+ future	=potential
6	Newaukum Creek	-	-	8%
7	Covington Creek	4%	4%	7%
8	Jenkins Creek	17%	11%	28%
9	Soos Creek	23%	21%	44%
10	Green RM 31.4 - 40.7	3%	5%	8%
11	Green RM 23.8 - 31.4	35%	13%	48%
12	Mill Creek	27%	14%	41%

Figure 8.1. Wastewater Treatment Service Areas

Base flow is largely a function of population served by the system. King County Wastewater Treatment Division (KCWTD) staff indicated that base sewage flows can be coarsely estimated from assumptions of 60 gallons per capita per day, 2.5 persons per household, and 4 households per acre, yielding 600 gallons per acre per day, on average, for sewered areas.[61]

I/I is highly variable, and is a function of weather conditions, the physical condition of the system and non-sewage connections. The definition of I/I from the "Joint WEF Manual Of Practice FD2 – ASCE Manual and Report On Engineering Practice No. 62" is: "*Infiltration is water that enters a sewer system from the ground through defective pipes, pipe joints, damaged lateral connections or manhole walls. Inflow is extraneous storm water that enters a sanitary sewer system through roof leaders, cleanouts, foundation drains sump pumps and cellar, yard and area drains.*"

KCWTD is undertaking a major, multi-year assessment of its regional wastewater system and provided this study with considerable detail on the extent of its service area within the study basins, as well as wastewater flow data based on long-term simulation modeling. KCWTD estimates of monthly average sewage flows from the study basins were accompanied by the documentation presented in the following two paragraphs.

> The monthly average volumes are based on 60-year continuous model runs using the first 60 years of the Pierce County Extended Time Series rainfall data set. The average volume was computed by accumulating the monthly volumes of the KCWTD model basins that lie within the Green River Water Quantity study area and dividing the accumulated volume by 60. The KCWTD model basins were calibrated with local measured rainfall to measured sewer flows for the months of November through January, 2000/2001, and 2001/2002. The calibration process involved establishing sewage flow patterns (diurnal flow) based on measured flow data from non-storm time periods and then calibrating the infiltration/inflow (I/I) portion of the model using the local rainfall data in addition to CALAMAR radar rainfall data for the storms. The Model used for the calibration and long-term runs is MOUSE produced by the Danish Hydraulic Institute (DHI).
>
> The KCWTD model basin volumes were apportioned to the Green River Water Quantity study area basins by determining the sewered area of the appropriate KCWTD model basin in each of the study area basins and then multiplying the modeled monthly volume by the ratio of the sewered area within the study area basin relative to the total sewered area of the model basin.

Figure 8.2 shows the monthly average wastewater flows exported from the study area to the King County South Treatment Plant, based on a 60-year simulation model calibrated to current conditions. For analysis purposes, wastewater exports to the Enumclaw treatment facility were estimated on the basis of year 2000 population within the study basin portion of the city[62], a base sewer flow of 60 gallons per capita per day, and I/I contributions equal to the average I/I percentages in the King County system. Table 8.4 summarizes the average annual wastewater exports from each of the study sub-basins.

[61] This coarse methodology for base flow estimation for wastewater does not distinguish between residential and workplace (employee) flows, and per-capita values are therefore not compatible with potable water supply methodologies which separately estimate each component of total demand.

[62] For Enumclaw, it was determined from city officials that the city provides wastewater treatment for a service area which corresponds closely to the city limits, but not the larger water service area. The population for the study area portion of the city was estimated from year 2000 census data.

Figure 8.2.
Wastewater Exports from Study Area to King County Regional Facility

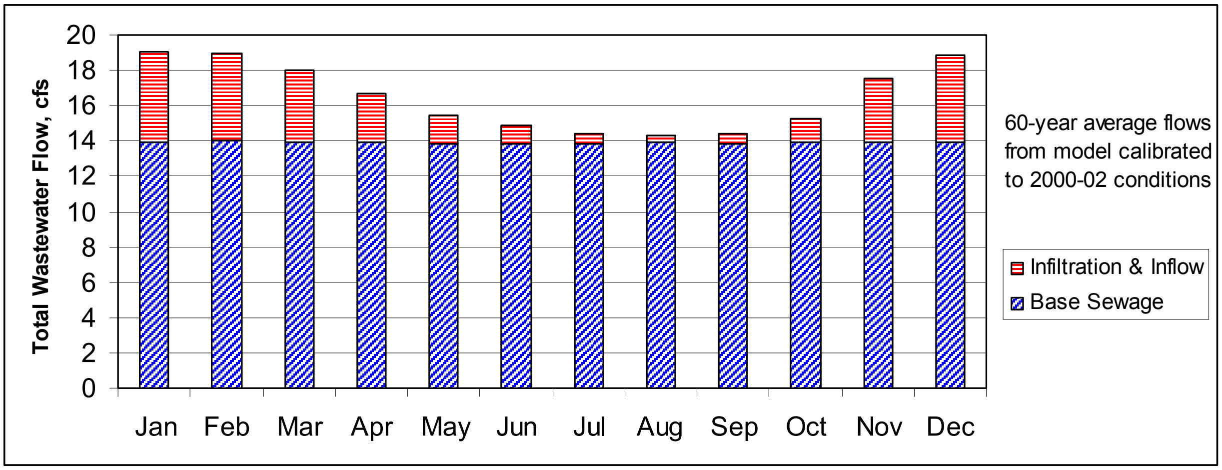


Table 8.4
Average Wastewater Exports under Current Conditions

Sub-Basin		Annual Sewage Flow		I/I as % of Total Sewage Flow		
ID	Name	MG	equiv cfs	Aug (min month)	Dec (max month)	Annual average
1-5	Green River above RM 40.7	0	0.0	-	-	-
6	Newaukum Creek	146*	0.6	-	-	-
7	Covington Creek	118	0.5	10.3%	31.5%	22.4%
8	Jenkins Creek	647	2.7	2.9%	33.5%	20.2%
9	Soos Creek	1,485	6.3	3.5%	28.8%	17.0%
10	Green River RM 31.4 - 40.7	161	0.7	1.5%	20.6%	10.9%
11	Green River RM 23.8 - 31.4	828	3.5	1.4%	22.4%	11.9%
12	Mill Creek	652	2.8	2.8%	23.2%	13.0%
1 - 12	Entire Study Area	3,891	17.1	2.9%	27.1%	15.7%

* Newaukum data are approximate.

9 Water Balance Assessment Summary

In this chapter, the individual water balance components which were assessed in the preceding chapters are aggregated to yield the total managed water fluxes which potentially affect flows at the streamflow analysis points. The fluxes of particular interest are the total extraction (withdrawals) and the total net water exports from the basin above each flow analysis point. These fluxes are compared to the current-condition streamflows to assess the magnitude and significance of managed water effects on streamflows.

Tables 9.1 and 9.2 summarize the water balance components affecting flows at streamflow analysis sites, expressed as mean annual values. Table 9.1 presents data for flow analysis points along the mainstem Green River; Table 9.2 presents data for flow analysis points on the major tributaries. To facilitate comparison, all water balance flux and streamflow values are presented in common units of cubic feet per second.

The data columns in Tables 9.1 and 9.2 correspond to the 12 streamflow analysis points—7 on the mainstem channel and 5 on tributary streams—which are described in Chapter 3. The data rows in Tables 9.1 and 9.2 correspond to the various water balance components which are described at length in Chapters 6, 7, and 8. Each of the data rows includes either a specific reference to the report section where a detailed description may be found, or a numeric formula to show how the data were computed from other values in the table.

Flow conditions in the reference year for which metered municipal withdrawal data were available (calendar year 2000) were slightly lower than average. Year 2000 flows for the Green River at Auburn were 76% of the long-term average since 1963 when Howard Hanson Dam became operational. Year 2000 flows on the gauged tributary streams (Soos, Newaukum, Jenkins, Covington) ranged from 77% to 83% of the 1988-2003 mean annual flows. It is not known how the water withdrawals reported for Year 2000 would compare to water withdrawals in a year of average or wet flows.

Three flow statistics reflecting current conditions are presented in Tables 9.1 and 9.2. These are: (1) mean annual flow for calendar year 2000; (2) the median flow for August; and (3) the 90% exceedance 7-day low flow for whichever month had the lowest flows. The mean annual flow data are from Table 3.1. The August and 7-day low flow statistics were extracted from Tables 3.2 through 3.13.

The most enlightening parts of Tables 9.1 and 9.2 are the final rows which compare water extractions and exports to the reference flow statistics. It should be noted that these comparison ratios are very simply determined and are presented solely to provide a general sense of the magnitude of the managed water fluxes in relation to the existing streamflows. Refinement to develop a more precise monthly accounting of the water budget components and streamflows was not attempted in the present work due to resource constraints and a lack of information to adequately address complexities in hydraulic continuity and time lag effects.

Table 9.1
Green River Flow Analysis Points
Basin Water Budget Components for Current Conditions
Annual Values in cubic feet per second (cfs) unless stated otherwise

Green River Mainstem Channel Analysis Point →	Below HHD	Near Palmer	In Gorge	Below Icy Ck Springs	Below Newau-kum Ck	Near Auburn	Below Mill Ck
River Mile	63.6	60.5	50.0	48.0	40.7	31.4	23.8
Sub-Basins above Analysis Point (Table 3.1)	1	1-2	1-3	1-4	1-6	1-10	1-12
Total Basin Area, square miles (Table 3.1)	222	231	253	275	310	397	419
Total Impervious Area, % of basin (Table 6.3)	1%	1%	2%	2%	3%	8%	10%
Precipitation and Recharge							
Annual Precipitation (Approx, Figure 6.3)	1,226	1,289	1,403	1,514	1,645	1,942	2,013
Annual Groundwater Recharge (Table 6.5)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Public Water System Extraction and Supply							
A - Year 2000 Extractions (Table 7.2)	6.8	94.2	94.3	94.7	98.2	116.6	123.2
B - Delivered Supply within Basin (Table 7.4)	0.0	0.0	0.1	0.2	2.3	18.3	28.7
Other Water Extraction and Use							
C - Self-Supplied Domestic (Table 7.5)	0.0	0.0	0.0	0.1	0.2	0.6	0.6
D - USGS-Reported Other Use (Table 7.6)	0.0	0.0	0.0	0.0	0.0	0.7	0.9
E - Possible Additional Use (Table 7.7)	0.0	0.0	0.0	0.1	0.5	4.5	6.2
F – Sum of Other Uses (C + D + E)	0.0	0.0	0.1	0.2	0.7	5.7	7.7
Exports and Adjustments							
G - Potable Water Exports (A-B; Table 8.3)	6.8	94.2	94.2	94.6	95.9	98.4	94.6
H - Wastewater Exports (Table 8.4)	0.0	0.0	0.0	0.0	0.6	10.8	17.1
I - Hydraulic Continuity (Table 8.2)	0.0	0.0	0.0	0.0	-0.3	-1.3	-1.7
Major Managed Water Fluxes							
J - Total Extractions (A + F + I)	6.8	94.2	94.4	94.9	98.7	121.0	129.3
K - Total Delivered Supply within Basin (B + F)	0.0	0.0	0.2	0.3	3.1	24.0	36.4
L - Total Net Exports (H + G)	6.8	94.2	94.2	94.6	96.5	109.2	111.7
Current Conditions Streamflows (Chapter 3)							
M - Average Flow in Calendar Year 2000	753	687	732	775	847	1,021	1,066
N - Median Monthly Flow in August	244	136	155	172	204	273	292
O - 90% Exceedance Min Monthly 7-Day Low	202	103	121	137	160	209	224
Total Extractions (J) compared to Current Condition Streamflows							
Extraction as % of Yr 2000 Avg Flow, J /(M+J)	1%	12%	11%	11%	10%	11%	11%
Extraction as % of Aug Median Flow, J /(N+J)	3%	41%	38%	36%	33%	31%	31%
Extraction as % of Min 7-Day Low, J /(O+J)	3%	48%	44%	41%	38%	37%	37%
Total Net Exports (L) compared to Current Conditions Streamflows							
Exports as % of Yr 2000 Avg Flow, L /(M+L)	1%	12%	11%	11%	10%	10%	9%
Exports as % of Aug Median Flow, L /(N+L)	3%	41%	38%	35%	32%	29%	28%
Exports as % of Min 7-Day Low, L / (O+L)	3%	48%	44%	41%	38%	34%	33%

Table 9.2
Tributary Stream Flow Analysis Points
Basin Water Budget Components for Current Conditions
Annual Values in cubic feet per second (cfs) unless stated otherwise

Tributary Stream Analysis Point→	Newaukum Creek nr Black Diamond	Covington Creek nr Mouth	Jenkins Creek nr Mouth	Soos Creek nr Mouth	Mill Creek nr Mouth
River Mile	0.9	1.2	0.4	1.1	0.3
Sub-Basins above Analysis Point (Table 3.1)	6	7	8	7-9	12
Total Basin Area, square miles (Table 3.1)	27.1	21.5	15.9	66.3	12.3
Total Impervious Area, % of basin (Table 6.3)	11%	20%	31%	28%	42%
Precipitation and Recharge					
Annual Precipitation (Approx, Figure 6.3)	100	76	55	227	38
Annual Groundwater Recharge (Table 6.5)	34	41	30	109	16
Public Water System Extraction and Supply					
A - Year 2000 Extractions (Table 7.2)	3.4	7.9	9.2	18.3	1.0
B - Delivered Supply within Basin (Table 7.4)	1.9	1.8	3.7	13.8	4.6
Other Water Extraction and Use					
C - Self-Supplied Domestic (Table 7.5)	0.1	0.1	0.1	0.3	0.0
D - USGS-Reported Other Use (Table 7.6)	0.0	0.0	0.3	0.4	0.1
E - Possible Additional Use (Table 7.7)	0.3	3.2	0.4	3.6	0.2
F - Sum of Other Uses (C + D + E)	0.4	3.2	0.8	4.3	0.3
Exports and Adjustments					
G - Potable Water Exports (A-B; Table 8.3)	1.4	6.1	5.6	4.5	-3.6
H - Wastewater Exports (Table 8.4)	0.6	0.5	2.7	9.5	2.8
I - Hydraulic Continuity (Table 8.2)	-0.3	-0.5	-0.3	-1.1	0.5
Major Managed Water Fluxes					
J - Total Extractions (A + F + I)	3.5	10.6	9.8	21.6	1.8
K - Total Delivered Supply within Basin (B + F)	2.3	5.0	4.4	18.1	4.9
L - Total Net Exports (H + G)	2.1	6.6	8.3	14.0	-0.8
Current Conditions Streamflows (Chapter 3)					
M - Average Flow in Calendar Year 2000	47	25	30	95	17
N - Median Monthly Flow in August	17	3	12	29	5
O – 90% Exceedance Min Monthly 7-Day Low	10	1	8	20	< 2
Total Extractions (J) compared to Current Condition Streamflows					
Extraction as % of Yr 2000 Avg Flow, J / (M+J)	7%	30%	25%	19%	9%
Extraction as % of August Median Flow, J / (N+J)	17%	78%	45%	43%	26%
Extraction as % of Min 7-Day Low, J / (O+J)	26%	91%	55%	52%	> 47%
Total Net Exports (L) compared to Current Conditions Streamflows					
Exports as % of Yr 2000 Avg Flow, L / (M+L)	6%	25%	25%	16%	-5%
Exports as % of August Median Flow, L / (N+L)	11%	69%	41%	33%	-20%
Exports as % of Min 7-Day Low, L / (O+L)	17%	87%	51%	41%	> -74%

The second-to-last block of rows in Tables 9.1 and 9.2 lists extractions (water withdrawals) as a percentage of the total streamflow which would exist before withdrawals if: (1) the extractions are in hydraulic continuity with the stream and result in reduced flows; (2) extractions occur at a constant year-round rate which would eliminate timing or lag effects; and (3) extraction amounts are for fully consumptive use with no flow being returned to the stream. Actual withdrawals match these conditions sufficiently closely to make the extraction-based comparison statistics meaningful as a coarse measure of managed water impacts on the streams.

The last block of rows in Tables 9.1 and 9.2 present net exports (Tacoma Water diversions, King County wastewater exports, etc.) as a percentage of the total streamflow which would exist before exports if: (1) the sources of the exported water are in hydraulic continuity with the stream and result in reduced streamflow; and (2) exports occur at a constant year-round rate which would eliminate timing or lag effects. Except for the Mill Creek basin, for which there are considerable net imports of water into the basin, actual exports match these conditions sufficiently closely to make the export-based comparison statistics meaningful as a coarse measure of managed water impacts on the streams.

The comparison statistics show that managed water impacts are discernable in all the study basins, with the largest impacts occurring, expectedly, during low flow conditions. The greatest impacts are in Covington Creek, then in Jenkins Creek, which are both tributaries to Soos Creek which ranks third. On Covington Creek, the analysis suggests that extractions (with an unknown return flow to the streams) and exports (which are fully consumptive use) have, in combination, caused approximately a 70% depletion of the natural-conditions median monthly flow in August, and approximately a 90% depletion of the 7-day low flows. A net depletion of the flow in the middle and lower Green River is also apparent, with extraction and export amounts ranging from about 10% of the total annual flow in 2000 to about 40% of the 7-day low flows. Of the studied streams, the least affected is Newaukum Creek for which extraction and export amounts are equivalent to about 6% of the mean annual flow in 2000 and about 20% of the 7-day low flows.

10 Alternative Management Actions for Water Quantity

The preceding chapters cover current conditions streamflows, flow sufficiency from a mainstem fishery perspective, land use effects, groundwater influences, and various managed water elements affecting water quantity issues in the Green River and its tributaries. This chapter focuses on alternative management actions to minimize further degradation of, and to improve, current water quantity conditions for habitat and fish.

Due to resource constraints, this study was not able to identify specific reaches and time periods for which modest (achievable) changes in available water would significantly benefit or harm fish populations. Such specificity would have enabled consideration of highly targeted management actions, including but not limited to source exchanges, aquifer recharge, special land use designations in the critical basin areas, and/or channel modifications to improve hydraulic characteristics during low flows. For example, the analysis has quantified the flows which currently exist in Covington Creek, and has concluded that current low flows, due to anthropogenic effects, are dramatically lower than under pristine basin conditions. However, the available resources were insufficient to take the next steps of translating the monthly and low-flow discharge data to channel hydraulic characteristics (depth, width, and velocity) meaningful to fish habitat, and identifying the reaches and time periods when water quantity is most limiting to viable fish populations.

It is apparent from the preceding chapters that there have been significant low flow reductions on the middle and lower Green River, and its major tributaries, due to water withdrawals and exports. Land cover change effects are likely responsible for an additional (but un-quantified) low flow reduction. For the mainstem Green River, the perception from a fish resource perspective is that the quantity of water now available for release to the Green River below the Tacoma diversion is insufficient to meet the needs of the multiple species using the river, and that it is vital to preserve and protect all remaining inflows below the Tacoma diversion. While a fisheries evaluation to specifically address flow sufficiency in the tributary channels has not yet been conducted, low flows have been identified as a limiting factor to fish passage in Soos and Newaukum Creeks.

Because of a lack of specificity in the time and place where improved hydraulic characteristics would be most beneficial to fish populations, our recommendations at this time consist of general Best Management Practices (BMPs) which can be widely applied so as to minimize further hydrologic alterations, and methods which are available to address reach-specific needs once those needs are defined.

The following alternative management actions include a brief description, potential instream flow benefits and potential benefits for fish.

1. Management of impervious surfaces and forest cover (landscape based) – Land cover in a watershed or catchment influences the magnitude, duration and frequency of runoff events and affects the overall water cycle (e.g., surface runoff, evapotranspiration, interflow and groundwater recharge). This is true at both the smaller tributary scale and larger river basin scale. By minimizing impervious surfaces and maximizing forest retention within a watershed, it is possible to minimize the impacts of land-use-related changes on streamflows, aquatic habitat, and salmonids.

Forest conversion to pasture, grass, or impervious surfaces in low-permeability till or clay soils generally results in reduction of evapotranspiration and groundwater recharge. This leads to greater peak flows during wet season rainfall events and reduction in base flows during the dry season and between runoff events. Natural water storage in wetlands and hummocky forested areas, which provide groundwater recharge over prolonged periods, is also reduced.

A somewhat different situation exists in areas of freely draining outwash soils. Provided that forest conversion is accompanied by opportunities for the complete infiltration of stormwater, land cover conversion can enhance recharge and hence water available for stream base flows. However, the potential benefits of this land cover change need to be weighed against the additional water withdrawals (and potential water exports) associated with the land use changes to residential and commercial development.

Minimizing the increase in impervious surfaces and maintaining forest cover where possible helps to maintain existing hydrology by limiting changes to groundwater recharge. Salmonids benefit by limiting changes to the natural flow regime to which they are uniquely adapted. Increases in peak flows can scour redds in spawning areas, increase sedimentation, or flush juvenile fish downstream prematurely. Lower flows can limit salmonid migration, dry up otherwise suitable spawning areas and reduce available rearing habitat. Reduction in groundwater flows can also affect salmonids by increasing water temperatures.

2. Water supply management options to benefit fish – Water withdrawals, whether by surface water diversion or groundwater extraction, have an effect on available water in streams and rivers. With increased awareness of life-cycle needs of salmonids in streams and rivers, it is possible to manage surface and groundwater withdrawals to reduce impacts on fish. This would include managing withdrawals during critical spawning, incubation or rearing periods. Management options include: (1) targeted seasonal reduction in withdrawals, (2) supplementing instream flows with conservation storage (streamflow augmentation), (3) source displacement or source exchange options (in which one source is substituted for another to benefit fish or use water diversions more efficiently), (4) interties (connecting adjacent water systems to allow exchange of water between them to move water where it is needed for both fish and people) or (5) supplementing flows with groundwater, sometimes called “pump and dump.”

The effect of surface water diversions and groundwater withdrawals on instream flows can be substantial, particularly during seasonal low flow conditions (see Table 9.2). The estimated water extraction in the five tributaries assessed in the Green River varied from 17 to 78 percent of median August monthly flows. Effects during drier years or localized effects on flow can be even greater. By managing flows using some of the techniques noted above, it would be possible to reduce the effects on dry season low flows. Salmonid benefits would include improved migration, greater access to suitable spawning areas and increased rearing habitat, including mainstem and off-channel areas. Generally, it would be preferable to reduce water withdrawals to enhance instream flows as a first option followed by streamflow augmentation, source displacement, or intertie options because it is more natural and maintains local water conditions. Source displacement, source exchange, and intertie options should be examined carefully on a case-by-case basis to assess the relative benefits and impacts from one system to another.

3. Stream morphometry management to “fit the habitat to the flow” – The Green River flow regime that existed historically has been substantially altered due to flood storage and water diversions. In addition, land use changes and river engineering works (e.g., levees, revetments) have affected floodplains and channel migration. The result of these changes is a river valley, floodplain, and river channel that do not “fit” the current flow regime. This management action could involve lowering the floodplain at select locations, and altering side channel and off-channel areas where feasible to improve connectivity and access for salmonids. This could be applied to the mainstem of the middle and lower Green River and key tributaries.

Prior to construction of Howard Hanson Dam in the early 1960s, peak annual flows exceeded 12,000 cfs as measured at Auburn in more than half of the years between the mid-1930s and early 1960s. Peak flows exceeded 18,000 cfs during five years, with a maximum of 28,000 cfs in 1959. As a result of flood control operations at the dam, peak flows are managed to stay below 12,000 cfs, greatly reducing the area of flooding and access to off-channel habitats. In addition, areas that inundated regularly during higher wet season flows are infrequently inundated under the current flow regime. Through changes to river channel, off-channel and floodplain morphometry, it would be possible to improve habitat conditions for salmonids. This might include expanded spawning area and rearing habitat, and improved connectedness with off-channel or tributary habitats.

4. Infiltration of stormwater – Historically, regular floodplain inundation resulted in groundwater infiltration and support of hyporheic flows to streams and rivers (Hyporheic flow is the percolating flow of water through the sand, gravel, and sediments under and beside a stream channel or floodplain that contributes water to the stream). The alluvial sand and gravel sediments associated with floodplain areas are expected to be permeable and should provide infiltration opportunities. By increasing floodplain infiltration of stormwater, where feasible, it is possible to increase base flow to streams and rivers and improve hydrologic continuity. This could be applied to the mainstem of the middle and lower Green River and key tributaries for new construction or by retrofitting existing stormwater systems. Opportunities for stormwater infiltration should, of course, be pursued wherever suitable conditions exist throughout the watershed. River floodplain areas are of particular interest because they may provide suitable infiltrative soils in protected areas not currently accessible to stormwater engineers.

Typical stormwater management relies on detention of peak flows prior to discharge to surface waters. In addition, areas developed prior to the adoption of adequate stormwater management requirements (before about 1990) often discharge with minimal detention. By harnessing this stormwater resource, it would be possible to improve floodplain and instream hydrologic conditions both seasonally and between rainfall events. Benefits to salmonids could include improved spawning habitat resulting from streambed upwelling, base flow maintenance, and cooler groundwater inflows.

5. Drought preparedness management guidelines – Guidelines could be developed as part of a Drought Response program[63] to protect instream resources (including habitat for salmonids) while addressing water supply needs for out-of-stream uses. Elements could include monitoring of demands, restriction strategies, overall conservation including plumbing upgrades, curtailment of non-essential uses, reduced water withdrawal, and events or actions that will trigger application of drought response programs.[64,65] By properly planning for droughts and anticipating alternative scenarios, it is possible to minimize the potential for extreme impacts on instream resources.

Dry water years and low flow conditions are part of natural conditions, but droughts can be exacerbated by water demands. Instream flows for future water rights in the Green-Duwamish river basin were established in chapter 173-509 WAC, including flows for "critical" water years. By preparing a drought response program, it will be possible to minimize potential effects of low flow on instream resources. Some of the impacts on salmonids likely to result from extreme low flow conditions include limits on

[63] For example, Tacoma Water has a Water Shortage Response Plan, updated in March 2005, that is designed to protect instream resources while addressing municipal water supply needs.

[64] New South Wales. 2004. Best Practice Management of Water Supply and Sewerage Guidelines (Appendix D – Drought Management).

[65] Central Puget Sound Initiative. 2002. Draft Central Puget Sound Regional Water Resources Strategy. October 15, 2002.

adult upstream migration, reduction of available spawning habitat, drying of redds after spawning, water temperature effects, and reduction in area of available rearing habitat. Adequate planning for salmonid needs during drought conditions can help reduce these potential impacts.

6. Maintain functioning septic systems where feasible – Septic systems are usually the wastewater treatment system of choice for lots that are ½-acre or larger. By maintaining functioning septic systems in quasi-suburban and rural areas, it helps protect natural hydrologic conditions. The use of septic systems ensures that water for household purposes gets infiltrated back into the ground locally. When developed areas become served by sewer systems, wastewater is usually exported from the basin, contributing to overall reduction of base flows and groundwater recharge. It is important to note that in some instances, septic systems may result in nutrient enrichment or elevated bacterial levels that should be considered with respect to this potential action.

Benefits of maintaining septic systems include groundwater recharge and base flow supplementation. This helps maintain baseflows year-round and can contribute to dry season low flows. Benefits are cumulative across a larger area from localized infiltration. Salmonid benefits could include improved migration, and support of summer rearing habitats.

7. Develop uses for reclaimed wastewater to reduce water demand –Reclaimed wastewater is water that gets treated to such a high level that it can be used safely and effectively for non-drinking water purposes such as landscape and agricultural irrigation, heating and cooling, and industrial processing. Reclaimed water is available year-round, even during dry summer months or when drought conditions can strain other water resources. King County's Regional Wastewater Services Plan[66] calls for expanding the production and use of reclaimed water as a valuable resource. Reclaimed water could potentially: (1) enhance or maintain fish runs consistent with the region's Endangered Species Act response, (2) supply additional water for the region's non-potable and indirect potable uses, and (3) preserve environmental and aesthetic values.

Greater use of reclaimed wastewater for irrigation and other consumptive uses can reduce the demand on freshwater supplies, particularly during drier low flow periods. This has the potential to leave more water in the streams for instream benefits, including improved adult upstream migration, maximizing available spawning habitat, maintaining flows during incubation of redds, and maximizing access to available rearing habitat.

8. Evaluate options for agreement with Tacoma Water to supply water for fish – Tacoma Water currently diverts up to 113 cfs from the Green River for municipal and industrial purposes as part of its first diversion water right claim. Plans to exercise a second water diversion right up to an additional 100 cfs (known as the Second Supply Project and Additional Water Storage Project at HHD) are nearing completion and will include storage of up to 20,000 additional acre-feet of water at Howard Hanson reservoir for municipal withdrawals[67]. Options for utilizing some of this additional stored water to meet the needs of fish could be pursued through a possible agreement with Tacoma Water. This could involve additional streamflow augmentation when allowed by shortfalls in demand, reduced spring storage to maintain target instream flows, or other arrangements. This effort should be considered in the context of Tacoma's existing agreement with the Muckleshoot Indian Tribe to guarantee instream flow targets at Auburn of 250 cfs in average to dry years and ongoing flow management efforts on the Green River.

---

[66] King County. 1999. Regional Wastewater Services Plan.

[67] Tacoma Water. 1999. Tacoma Water Habitat Conservation Plan. Green River Water Supply Operations and Watershed Protection. Public Review Draft.

As noted in Chapter 4, there are challenges in meeting instream flow needs during early summer through fall, including: (1) protection of wild winter steelhead redds through fry emergence, (2) adequate summer low flows for juvenile steelhead and salmon rearing, and (3) sufficient flows for Chinook spawning. Working with Tacoma Water to consider possible options for improved management of instream flows is an additional opportunity that could be pursued. This has the potential to provide more water for fish to improve upstream migration, maximize available spawning and rearing habitat, and maintain flows during incubation of redds. [Note: Tacoma Water has, for years, been actively involved with the Water Management coordination meetings to manage its water withdrawals to augment flow at critical times. Tacoma Water will continue this flexibility in the future within the constraints of meeting public water supply needs.]

The preceding alternative management actions are presented to stimulate discussion and consider options for improving water quantity conditions for fish. Some or all of these options could be pursued to varying degrees or in different geographic areas or sub-basins. No single action will solve the water quantity problem that salmonids face in particular sub-basins or specific years. However, if creative options are considered and implemented where feasible, it will be possible to cumulatively make a significant difference for salmonids in the Green River and its tributaries.

INDUSTRIAL STORMWATER

FACT SHEET SERIES

Sector M: Automobile Salvage Yards

U.S. EPA Office of Water
EPA-833-F-06-028
December 2006

What is the NPDES stormwater permitting program for industrial activity?

Activities, such as material handling and storage, equipment maintenance and cleaning, industrial processing or other operations that occur at industrial facilities are often exposed to stormwater. The runoff from these areas may discharge pollutants directly into nearby waterbodies or indirectly via storm sewer systems, thereby degrading water quality.

In 1990, the U.S. Environmental Protection Agency (EPA) developed permitting regulations under the National Pollutant Discharge Elimination System (NPDES) to control stormwater discharges associated with eleven categories of industrial activity. As a result, NPDES permitting authorities, which may be either EPA or a state environmental agency, issue stormwater permits to control runoff from these industrial facilities.

What types of industrial facilities are required to obtain permit coverage?

This fact sheet specifically discusses stormwater discharges from automobile salvage yards as defined by Standard Industrial Classification (SIC) and includes battery reclaimers, salvage yards, and automobile recyclers (Primary SIC 5015). Facilities and products in this group fall under the following categories, all of which require coverage under an industrial stormwater permit:

- Activities related to dismantling of used motor vehicles for the purpose of selling parts
- Wholesale or retail distribution of used motor vehicle parts

What does an industrial stormwater permit require?

Common requirements for coverage under an industrial stormwater permit include development of a written stormwater pollution prevention plan (SWPPP), implementation of control measures, and submittal of a request for permit coverage, usually referred to as the Notice of Intent or NOI. The SWPPP is a written assessment of potential sources of pollutants in stormwater runoff and control measures that will be implemented at your facility to minimize the discharge of these pollutants in runoff from the site. These control measures include site-specific best management practices (BMPs), maintenance plans, inspections, employee training, and reporting. The procedures detailed in the SWPPP must be implemented by the facility and updated as necessary, with a copy of the SWPPP kept on-site. The industrial stormwater permit also requires collection of visual, analytical, and/or compliance monitoring data to determine the effectiveness of implemented BMPs. For more information on EPA's industrial stormwater permit and links to State stormwater permits, go to www.epa.gov/npdes/stormwater and click on "Industrial Activity."

What pollutants are associated with my facility's activities?

Pollutants conveyed in stormwater discharges from automobile salvage yards will vary. There are a number of factors that influence to what extent industrial activities and significant materials can affect water quality.

- Geographic location
- Topography
- Hydrogeology
- Extent of impervious surfaces (i.e., concrete or asphalt)
- Type of ground cover (e.g., vegetation, crushed stone, or dirt)
- Outdoor activities (e.g., material storage, loading/unloading, vehicle maintenance)
- Size of the operation
- Type, duration, and intensity of precipitation events

The activities, pollutant sources, and pollutants detailed in Table 1 are commonly found at automobile salvage yards.

Table 1. Common Activities, Pollutant Sources, and Associated Pollutants at Automobile Salvage Yards

Activity	Pollutant Source	Pollutant
Vehicle Dismantling	Oil, anti-freeze, batteries, gasoline, diesel fuel, hydraulic fluids, electrical switches	Oil and grease, ethylene glycol, heavy metals, mercury
Used Parts Storage	Batteries, chrome bumpers, wheel balance weights, tires, rims, filters, radiators, catalytic converters, engine blocks, hub caps, doors, drivelines, galvanized metals, mufflers	Sulfuric acid, galvanized metals, oil and grease, heavy metals, petroleum hydrocarbons, total suspended solids (TSS)
Outdoor Vehicle and Equipment Storage	Leaking engines, chipping/corroding bumpers, chipping paint, galvanized metal	Oil and grease, arsenic, organics, heavy metals, total suspended solids (TSS)
Vehicle and Equipment Maintenance	Parts cleaning	Chlorinated solvents, oil and grease, heavy metals, acid/alkaline wastes
	Waste disposal of greasy rags, oil filters, air filters, batteries, hydraulic fluids, transmission fluids, radiator fluids, degreasers	Oil, heavy metals, chlorinated solvents, acid/alkaline wastes oil, heavy metals, chlorinated solvents, acid/alkaline wastes, ethylene glycol
	Spills of oil, degreasers, hydraulic fluids, transmission fluid, and radiator fluids	Oil, arsenic, heavy metals, organics, chlorinated solvents, ethylene glycol
	Fluids replacement, including oil, hydraulic fluids, transmission fluid, and radiator fluids	Oil, arsenic, heavy metals, organics, chlorinated solvents, ethylene glycol
Vehicle, Equipment, and Parts Washing Areas	Washing and steam cleaning waters	Oil and grease, detergents, heavy metals, chlorinated solvents, phosphorus, salts, suspended solids
Liquid Storage in Above Ground Storage Tanks	External corrosion and structural failure	Fuel, oil and grease, heavy metals, materials being stored
	Installation problems	
	Spills and overfills due to operator error	
Illicit Connection to Storm Sewer	Sanitary water	Bacteria, biochemical oxygen demand (BOD), suspended solids
	Floor drains	Oil and grease, heavy metals, chlorinated solvents, fuel, ethylene glycol
	Vehicle washwaters	Oil and grease, detergents, metals, chlorinated solvents, phosphorus, suspended solids
	Radiator flushing wastewater	Ethylene glycol
	Leaking underground storage tanks	Materials stored or previously stored

What BMPs can be used to minimize contact between stormwater and potential pollutants at my facility?

A variety of BMP options may be applicable to eliminate or minimize the presence of pollutants in stormwater discharges from automobile salvage yards. You will likely need to implement a combination or suite of BMPs to address stormwater runoff at your facility. Your first consideration should be for pollution prevention BMPs, which are designed to prevent or minimize pollutants from entering stormwater runoff and/or reduce the volume of stormwater requiring management. Prevention BMPs can include regular cleanup, collection and containment of debris in storage areas, and other housekeeping practices, spill control, and employee training. It may also be necessary to implement treatment BMPs, which are engineered structures, intended to treat stormwater runoff and/or mitigate the effects of increased stormwater runoff peak rate, volume, and velocity. Treatment BMPs are generally more expensive to install and maintain and include oil-water separators, wet ponds, and proprietary filter devices.

The management practices discussed herein are well suited mechanisms to prevent or control the contamination of stormwater discharges associated with automobile salvage yards. In general, it is important to develop a stormwater management policy statement, review the policy with employees, and keep it posted. Additionally, identifying weaknesses in current facility practices will aid the permittee in determining appropriate BMPs that will achieve a reduction in pollutant loadings.

All facilities should implement BMPs in the following areas of the site:

- Vehicle dismantling and maintenance areas
- Vehicle, parts, and equipment storage areas
- Material storage areas
- Vehicle, parts, and equipment cleaning areas

Mercury switch used in vehicle. Be aware: specific permit requirements may vary according to permitting authority so it is important to reference the requirements applicable of the state in which your facility is located. For instance, many states are now addressing the issue of mercury switch removal to prevent mercury releases that occur from automobile recycling. Mercury switches have been used until recently for hood, trunk, or door lights.

BMPs must be selected and implemented to address the following:

Good Housekeeping Practices

Good housekeeping is a practical, cost-effective way to maintain a clean and orderly facility to prevent potential pollution sources from coming into contact with stormwater. It includes establishing protocols to reduce the possibility of mishandling materials or equipment and training employees in good housekeeping techniques. Common areas where good housekeeping practices should be followed include trash containers and adjacent areas, material storage areas, vehicle and equipment maintenance areas, and loading docks. Good housekeeping practices must include a schedule for regular pickup and disposal of garbage and waste materials and routine inspections of drums, tanks, and containers for leaks and structural conditions. Practices also include containing and covering garbage, waste materials, and debris. Involving employees in routine monitoring of housekeeping practices has proven to be an effective means of ensuring the continued implementation of these measures.

Minimizing Exposure

Where feasible, minimizing exposure of potential pollutant sources to precipitation is an important control option. Minimizing exposure prevents pollutants, including debris, from coming into contact with precipitation and can reduce the need for BMPs to treat contaminated stormwater runoff. It can also prevent debris from being picked up by stormwater and carried into drains and surface waters. Examples of BMPs for exposure minimization include covering materials or activities with temporary structures (e.g., tarps) when wet weather is expected or moving materials or activities to existing or new permanent structures (e.g., buildings, silos, sheds). Even the simple practice of keeping a dumpster lid closed can be a very effective pollution prevention measure.

Erosion and Sediment Control

BMPs must be selected and implemented to limit erosion on areas of your site that, due to topography, activities, soils, cover, materials, or other factors are likely to experience erosion. Erosion control BMPs such as seeding, mulching, and sodding prevent soil from becoming dislodged and should be considered first. Sediment control BMPs such as silt fences, sediment ponds, and stabilized entrances trap sediment after it has eroded. Sediment control BMPs should be used to back-up erosion control BMPs.

Management of Runoff

Your SWPPP must contain a narrative evaluation of the appropriateness of stormwater management practices that divert, infiltrate, reuse, or otherwise manage stormwater runoff so as to reduce the discharge of pollutants. Appropriate measures are highly site-specific, but may include, among others, vegetative swales, collection and reuse of stormwater, inlet controls, snow management, infiltration devices, and wet retention measures.

A combination of preventive and treatment BMPs will yield the most effective stormwater management for minimizing the offsite discharge of pollutants via stormwater runoff. Though not specifically outlined in this fact sheet, BMPs must also address preventive maintenance records or logbooks, regular facility inspections, spill prevention and response, and employee training.

Specific runoff management practices for automobile salvage facilities include the installation/use of:

- Berms or drainage ditches on the property line (to prevent run-on from neighboring properties
- Berms for uncovered outdoor storage of soiled parts, engine blocks, and above-ground liquid storage
- Detention ponds
- Filtering devices and oil/water separators

All BMPs require regular maintenance to function as intended. Some management measures have simple maintenance requirements, others are quite involved. You must regularly inspect all BMPs to ensure they are operating properly, including during runoff events. As soon as a problem is found, action to resolve it should be initiated immediately.

Implement BMPs, such as those listed below in Table 2 for the control of pollutants at automobile salvage yards, to minimize and prevent the discharge of pollutants in stormwater. Identifying weaknesses in current facility practices will aid the permittee in determining appropriate BMPs that will achieve a reduction in pollutant loadings. BMPs listed in Table 2 are broadly applicable to automobile salvage yards; however, this is not a complete list and you are recommended to consult with regulatory agencies or a stormwater engineer/consultant to identify appropriate BMPs for your facility.

Table 2. BMPs for Potential Pollutant Sources at Automobile Salvage Yards

Activity	BMPs
Dismantling and vehicle maintenance	Minimize exposure ❑ Installation of a consolidated processing area, including a covered and bermed impermeable concrete surface equipped with a drain, where all fluids are drained. Fluid and Parts Removal ❑ Drain all fluids from vehicles upon arrival at the site. Segregate the fluids and properly store or dispose of them. ❑ Drain oil filters (and all vehicle parts) before disposal or recycling.

Table 2. BMPs for Potential Pollutant Sources at Automobile Salvage Yards (continued)

Activity	BMPs
Dismantling and vehicle maintenance (continued)	Fluid and Parts Removal (continued) ❑ Inspect vehicles for leaks as soon as possible once they arrive on-site. Inspect vehicles quarterly for signs of leakage. Check for unwanted material that could have been placed in the vehicle. ❑ When pulling parts from vehicles in the yard, employ a catch sled or tray to recover the majority of fluids which will be released. Place drip pans, large plastic sheets, or canvas under vehicles or equipment during maintenance and dismantling activities. Where drip pans are used, they should not be left unattended to prevent accidental spills. ❑ Engine oil should be drained and stored in clearly labeled tanks or containers. Tanks and containers must be kept in good operating condition, free of any visible spills or leaks, structural damage, or deterioration. ❑ Remove battery as soon as feasible after vehicle enters the facility. ❑ Promptly transfer used fluids to the proper container. ❑ Empty and clean drip pans and containers; do not leave full drip pans or other open containers around the shop. ❑ Remove all mercury switches as soon as possible making sure not to puncture the mercury container during removal. Ship switches to End of Life Vehicle Solutions (ELVS). Vehicle Processing ❑ Maintain an organized inventory of materials used in the maintenance shop. ❑ Designate one person to keep track of parts in the yard. As soon as a hulk is salvaged to its minimum extent, it should be processed for shredding to minimize the dripping of fluids and clutter in the yard. Material Storage ❑ Nonhazardous substances that are contaminated with a hazardous substance are considered a hazardous substance. ❑ Store cracked batteries in a nonleaking secondary container. ❑ Keep waste streams separate (e.g., waste oil and mineral spirits). Recycling and Disposal ❑ Recycle anti-freeze, gasoline, used oil, mineral spirits, windshield washer fluid, and solvents. ❑ Label and track the recycling of waste material (e.g., used oil, spent solvents, and batteries). ❑ Dispose of greasy rags, oil filters, air filters, batteries, spent coolant, and degreasers properly. Discharges ❑ Know where your sumps and drains discharge to. Do not pour liquid waste down floor drains, sinks, or outdoor storm drain inlets. ❑ Plug floor drains that are connected to the storm or sanitary sewer. If necessary, install a sump that is pumped regularly. ❑ Screen out sludges and solids before they reach the waste sump. Use an absorbent pad around the perimeter of sumps to prevent unwanted hazardous materials from entering. ❑ Prohibit the practice of hosing down the shop floor, using dry cleanup methods, and/or collecting the stormwater runoff from the maintenance area and providing treatment. ❑ Treat stormwater discharges with devices such as oil-water separators.
Outdoor vehicle, equipment, and parts storage	Minimizing Exposure ❑ Cover all storage areas with a permanent cover (e.g., roofs) or temporary cover (e.g., canvas tarps). ❑ Store lead parts in a covered container that is capable of handling the excessive weight of lead. If storing lead tire weights with batteries, make sure weights are not placed under batteries or allowed to roll around as that could puncture batteries.

Table 2. BMPs for Potential Pollutant Sources at Automobile Salvage Yards (continued)

Activity	BMPs
Outdoor vehicle, equipment, and parts storage (continued)	Runoff Minimization ❑ Install curbing, berms, or dikes around storage areas. ❑ Install berms or drainage ditches on the property line. ❑ Install berms for uncovered outdoor storage of oily parts, engine blocks, and above ground liquid storage. ❑ Install filtering devices and oil/water separators. ❑ Use drip pans, large sheets of plastic, or canvas under all vehicles and equipment waiting for and during maintenance. ❑ Store mercury switches in covered, leak-proof containers in a way that prevents the glass capsule from breaking. (Manage mercury switches as hazardous waste. Containers should be labeled with "Hazardous Waste - Spent Mercury Switches") ❑ Use secondary containment for stored liquids such as oil, gas, and antifreeze, as well as for lead acid batteries. Good Housekeeping ❑ Tank storage should be secured and locked. ❑ Do not stockpile old tires as they are both a fire hazard and a breeding ground for mosquitoes and rodents. Use indoor tire racks. ❑ Confine storage of parts, equipment, and vehicles to designated areas. ❑ Vehicles of similar make and model should be located in a common area. Vehicles whose parts have higher demand should be in a common area and easily accessible. ❑ Repair malfunctioning equipment that is responsible for any leak or spill as soon as possible. ❑ Store batteries on impervious surfaces. Store batteries inside on a pallet or outside in a leak proof container. Curb, dike, or berm this area.
Vehicle, equipment, and parts washing areas	❑ Designate an area for cleaning activities. ❑ Perform all parts cleaning operations indoors or cover and berm outside cleaning areas. ❑ Clean parts using minimal amounts of solvents or detergents. ❑ Recycle and reuse cleaning fluids where practical. ❑ Use phosphate-free biodegradable detergents. ❑ Use detergent-based or water-based cleaning systems in place of organic solvent degreasers. ❑ Contain steam cleaning washwaters or discharge under an applicable NPDES permit. ❑ Ensure that washwaters drain well. ❑ Inspect cleaning area regularly. ❑ Install curbing, berms, or dikes around cleaning areas. ❑ Remove or deploy airbags prior to crushing or other maintenance activities. ❑ Be certain all fluids have been drained from vehicle prior to crushing. ❑ Fluid should be collected in a covered container, tested, and disposed of accordingly.
Vehicle crushing activities	❑ Capture crusher fluids to prevent spillage. Collect this mixture of fluids in a spill-proof covered container and dispose of it properly. It should not be allowed to drain onto the ground. Keep the drain within the crusher clean so that the fluids do not collect and overflow from the crusher onto the ground.

Table 2. BMPs for Potential Pollutant Sources at Automobile Salvage Yards (continued)

Activity	BMPs
Vehicle crushing activities (continued)	❑ Installation of an engineering fabric, such as geotextiles, followed by gravel, or a bermed impermeable concrete surface would be ideal as a foundation under the crusher. ❑ Develop a preventative maintenance program that involves timely inspections and/or maintenance of the crusher and facility equipment and vehicles. ❑ Keep the crusher equipment clean.
Automotive wastes	❑ Fuel - Drain fuel tanks, using air or hand pumps, into double-walled storage tanks. "Good" fuels can be reused on-site; "bad" fuels must be disposed of. ❑ Antifreeze - Reclaim and re-use, if possible. ❑ Freon (CFCs) - Voluntarily recapture, in anticipation of new regulations. ❑ Used motor oil - Drain and store in double-walled tanks. Re-use on-site or send offsite for refining/fuel blending. Accepted practice to leave oil in the engine during storage. Oil filters should drain for 24-hours. Empty filters return to vehicle for scrap metal reclamation. ❑ Other fluids and oils - Drain as completely as mechanically possible. Do not burn used oil unless approved. ❑ Asbestos Brake Shoes and Clutches - If handled, should be wetted down to prevent asbestos particulates from becoming airborne. ❑ Mercury switches - Remove promptly and avoid breakage. Store as hazardous waste. ❑ Do not use vehicle fluids, oil, or fuels for dust or weed control.
Liquid storage in above ground containers	❑ Maintain good integrity of all storage containers. ❑ Install safeguards (such as diking, berming, or permanent secondary containment) against accidental releases at the storage area. ❑ Valves on permanent secondary containment should be kept in the "off" position and locked at all times, except when collected water is removed. ❑ Inspect storage tanks to detect potential leaks and perform preventive maintenance. ❑ Inspect piping systems (pipes, pumps, flanges, couplings, hoses, and valves) for failures or leaks.
Illicit connection to storm sewer	❑ Plug all floor drains if it is unknown whether the connection is to storm sewer or sanitary sewer systems. Alternatively, install a sump that is pumped regularly. ❑ Perform dye testing to determine if interconnections exist between sanitary water system and storm sewer system. ❑ Update facility schematics to accurately reflect all plumbing connections. ❑ Install a safeguard against vehicle washwaters and parts cleaning waters entering the storm sewer unless permitted. ❑ Maintain and inspect the integrity of all underground storage tanks; replace when necessary.

What if activities and materials at my facility are not exposed to precipitation?

The industrial stormwater program requires permit coverage for a number of specified types of industrial activities. However, when a facility is able to prevent the exposure of ALL relevant activities and materials to precipitation, it may be eligible to claim no exposure and qualify for a waiver from permit coverage.

If you are regulated under the industrial permitting program, you must either obtain permit coverage or submit a no exposure certification form, if available. Check with your permitting authority for additional information as not every permitting authority program provides no exposure exemptions.

Where do I get more information?

For additional information on the industrial stormwater program see **www.epa.gov/npdes/stormwater/msgp**.

A list of names and telephone numbers for each EPA Region or state NPDES permitting authority can be found at **www.epa.gov/npdes/stormwatercontacts**.

References

Information contained in this Fact Sheet was compiled from EPA's past and present Multi-Sector General Permits and from the following sources:

- Automotive Recyclers Association. 2000. "Stormwater Best Management Practices."
  http://ara.timberlakepublishing.com/content.asp?pl=430&sl=468&contentid=474
- City of Phoenix, Street Transportation Department, Storm Water Management Section. 2004. Prevent Stormwater Contamination Best Management Practices for Section M - Automotive Salvage Yards. SIC Code: 5015.
  http://phoenix.gov/STREETS/ausalya5.pdf
- Delaware Department of Natural Resources and Environmental Control, Division of Air and Waste Management: Solid and Hazardous Waste. 2000. Salvage Yard Manual.
  www.dnrec.state.de.us/dnrec2000/divisions/awm/hw/hw/salvage.htm
- Florida Department of Environmental Protection and Florida Auto Dismantlers and Recyclers Association. 2002. Florida Green Yards, An Environmental Compliance Workbook for Automotive Recyclers.
  www.dep.state.fl.us/central/Home/Green_Yards/Compliance_Wkb_SalvageYards.pdf
- Environmental Compliance for Automotive Recyclers. 2005.
  www.ecarcenter.org
- Michigan Department of Environmental Quality.1999. Guide for Salvage Yard Owners.
  www.deq.state.mi.us/documents/deq-ead-tas-salvyard.pdf
- Monroe County Small Business Pollution Prevention Task Group and New York State Department of Environmental Conservation. "Auto Recyclers Guide to a Cleaner Environment – Best Management Practices."
- Northeast Waste Management Officials' Association. "P2Rx Topic Hub: Mercury–Automotive Table of Contents."
  www.newmoa.org/prevention/topichub/toc.cfm?hub=104&subsec=7&nav=7
- Sustainable Conservation. "Auto Recycling Project Overview."
  www.suscon.org/autorecycling/index.asp
- Sustainable Conservation. "Stormwater Management: A Guide for Auto Recycler Owners and Operators."
  www.suscon.org/autorecycling/pdfs/autorecycling_factsheet_english.pdf

- U.S. EPA – Region 8 Hazardous Waste Management Division, Hazardous Waste Minimization Program. 1995. EnviroSense Fact Sheet: Pollution Prevention Opportunities for the Automotive Recycling Industry.
  http://es.epa.gov/techinfo/facts/epa/epa-fs.html
- U.S. EPA, Office of Science and Technology. 1999. Preliminary Data Summary of Urban Stormwater Best Management Practices. EPA-821-R-99-012
  www.epa.gov/OST/stormwater
- U.S. EPA. The National Vehicle Mercury Switch Recovery Program.
  www.epa.gov/mercury/switch.htm
- U.S. EPA, Office of Wastewater Management. *NPDES Stormwater Multi-Sector General Permit for Industrial Activities (MSGP)*.
  www.epa.gov/npdes/stormwater/msgp
- VT Solid Waste Districts and Alliances, VT Department of Environmental Conservation, Environmental Assistance Division. Best Management Practices (BMP) for Vermont's Auto Salvage Yards.
  www.anr.state.vt.us/DEC/ead/sbcap/salvage/PDF/bmpguide.pdf

PHOTO ADDENDUM - SPECIALTY INTEREST AUTO WORKS, INC 4/1/13

#7 **DESCRIPTION:** SPILLS ARE OUTSIDE THE SECONDARY CONTAINMENT AREA. ALSO, 5-GALLON CONTAINER PLACED OUTSIDE CONTAINMENT AREA.

#8 **DESCRIPTION:** TIRE PILE ON FRESH GRAVEL

#9 **DESCRIPTION:** GRADED AND BERMED ALONG THE WESTERN PORTION

#10 **DESCRIPTION:** FRESH GRAVEL APPLIED TO MUCH OF THE SITE.

#11 **DESCRIPTION:** SPILLS AND DRIPS ON FRESH GRAVEL NOT CLEANED UP.

#12 **DESCRIPTION:** 55-GALLON CONTAINER OF WASTE OIL PLACED NEXT TO BAY DOOR.

Groundwater Hydrology

SECOND EDITION

David Keith Todd
UNIVERSITY OF CALIFORNIA, BERKELEY
and
DAVID KEITH TODD,
CONSULTING ENGINEERS, INC.

JOHN WILEY & SONS
New York • Chichester • Brisbane • Toronto • Singapore

Note that the tabulated values cover the following conditions below the hole: a shallow impermeable layer, an infinite homogeneous stratum, and a shallow, highly permeable (gravel) layer. The value y should correspond to that when dy/dt is measured.

Several other techniques similar to the auger hole test have been developed in which water level changes are measured after an essentially instantaneous removal or addition of a volume of water. With a small-diameter pipe driven into the ground, K can be found by the piezometer, or tube, method.[65] For wells in confined aquifers, the slug method can be employed.[12,41] Here a known volume of water is suddenly injected or removed from a well after which the decline or recovery of the water level is measured in the ensuing minutes. Where a pump is not available to conduct a pumping test on a well, the slug method serves as an alternative approach.

Pumping Tests of Wells. The most reliable method for estimating aquifer hydraulic conductivity is by pumping tests of wells. Based on observations of water levels near pumping wells, an integrated K value over a sizable aquifer section can be obtained. Then, too, because the aquifer is not disturbed, the reliability of such determinations is superior to laboratory methods. Pump test methods and computations are described in Chapter 4.

Anisotropic Aquifers

The discussion of hydraulic conductivity heretofore assumed that the geologic material was homogeneous and isotropic, implying that the value of K was the same in all directions. In fact, however, this is rarely the case, particularly for undisturbed unconsolidated alluvial materials. Instead, *anisotropy* is the rule where directional properties of hydraulic conductivity exist. In alluvium this results from two conditions. One is that individual particles are seldom spherical so that when deposited underwater they tend to rest with their flat sides down. The second is that alluvium typically consists of layers of different materials, each possessing a unique value of K. If the layers are horizontal, any single layer with a relatively low hydraulic conductivity causes vertical flow to be retarded, but horizontal flow can occur easily through any stratum of relatively high hydraulic conductivity. Thus, the typical field situation in alluvial deposits is to find a hydraulic conductivity K_x in the horizontal direction that will be greater than a value K_z in a vertical direction.

Consider an aquifer consisting of two horizontal layers, each individually isotropic, with different thicknesses and hydraulic con-

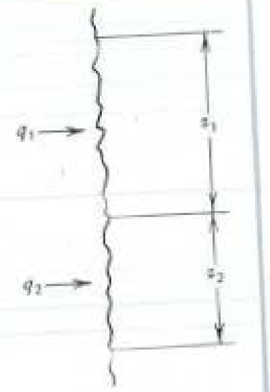


Fig. 3.7 Diagram c
isotropic, with diff
conductivities.

ductivities, as shown in F
layers, the flow q_1 in the

where i is the hydraulic g
Fig. 3.7. Because i must be
if follows that the total h

$q_x = ($

For a homogeneous syste

where K_x is the horizonta
tem. Equating these and

which can be generalized

$K_x =$

This defines the equivale
stratified material.

owing conditions below
n infinite homogeneous
gravel) layer. The value
measured.
uger hole test have been
re measured after an es-
n of a volume of water.
ground. K can be found
wells in confined aqui-
Here a known volume of
m a well after which the
measured in the ensuing
conduct a pumping test
lternative approach.

eliable method for esti-
by pumping tests of wells.
ar pumping wells, an inte-
on can be obtained. Then,
the reliability of such de-
thods. Pump test methods
ter 4.

fers

ity heretofore assumed that
and isotropic, implying that
tions. In fact, however, this
sturbed unconsolidated al-
the rule where directional
ist. In alluvium this results
vidual particles are seldom
water they tend to rest with
t alluvium typically consists
ssessing a unique value of K.
layer with a relatively low
flow to be retarded, but hori-
ny stratum of relatively high
cal field situation in alluvial
ivity K_x in the horizontal di-
K_z in a vertical direction.
vo horizontal layers, each in-
icknesses and hydraulic con-

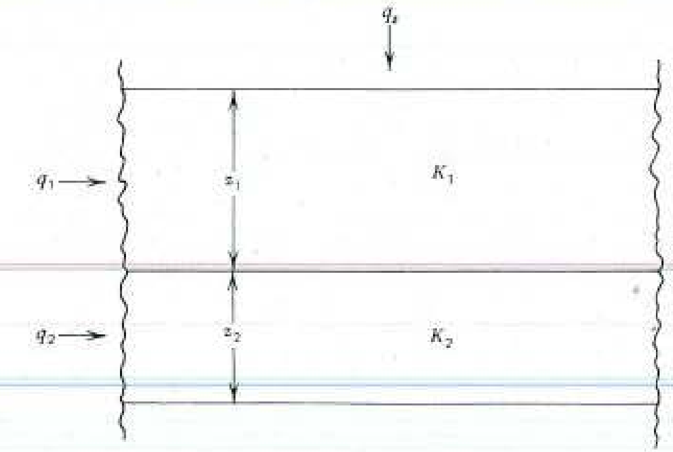


Fig. 3.7 Diagram of two horizontal strata, each isotropic, with different thicknesses and hydraulic conductivities.

ductivities, as shown in Fig. 3.7. For horizontal flow parallel to the layers, the flow q_1 in the upper layer per unit width is

$$q_1 = K_1 i z_1 \tag{3.25}$$

where i is the hydraulic gradient and K_1 and z_1 are as indicated in Fig. 3.7. Because i must be the same in each layer for horizontal flow, it follows that the total horizontal flow q_x is

$$q_x = q_1 + q_2 = i(K_1 z_1 + K_2 z_2) \tag{3.26}$$

For a homogeneous system this would be expressed as

$$q_x = K_x i(z_1 + z_2) \tag{3.27}$$

where K_x is the horizontal hydraulic conductivity for the entire system. Equating these and solving for K_x yields

$$K_x = \frac{K_1 z_1 + K_2 z_2}{z_1 + z_2} \tag{3.28}$$

which can be generalized for n layers as

$$K_x = \frac{K_1 z_1 + K_2 z_2 + \ldots + K_n z_n}{z_1 + z_2 + \ldots + z_n} \tag{3.29}$$

This defines the equivalent horizontal hydraulic conductivity for a stratified material.

Now, for vertical flow through the two layers in Fig. 3.7, the flow q_z per unit horizontal area in the upper layer is

$$q_z = K_1 \frac{dh_1}{z_1} \tag{3.30}$$

where dh_1 is the head loss within the first layer. Solving for the head loss

$$dh_1 = \frac{z_1}{K_1} q_z \tag{3.31}$$

From continuity q_z must be the same for the other layer so that the total head loss

$$dh_1 + dh_2 = \left[\frac{z_1}{K_1} + \frac{z_2}{K_2}\right] q_z \tag{3.32}$$

In a homogeneous system

$$q_z = K_z \left[\frac{dh_1 + dh_2}{z_1 + z_2}\right] \tag{3.33}$$

where K_z is the vertical hydraulic conductivity for the entire system. Rearranging,

$$dh_1 + dh_2 = \left[\frac{z_1 + z_2}{K_z}\right] q_z \tag{3.34}$$

and equating with Eq. 3.32,

$$K_z = \frac{z_1 + z_2}{\dfrac{z_1}{K_1} + \dfrac{z_2}{K_2}} \tag{3.35}$$

which can be generalized for n layers as

$$K_z = \frac{z_1 + z_2 + \ldots + z_n}{\dfrac{z_1}{K_1} + \dfrac{z_2}{K_2} + \ldots + \dfrac{z_n}{K_n}} \tag{3.36}$$

This defines the equivalent vertical hydraulic conductivity for a stratified material.

As mentioned earlier, the horizontal hydraulic conductivity in alluvium is normally greater than that in the vertical direction. This observation also follows from the above derivations; thus, if

$$K_x > K_z \tag{3.37}$$

then for the two-layer case f

$\frac{K_1 z_1 +}{z_1 +}$

which reduces to[42]

$\frac{z_1}{z_2}($

Because the left side is alway
thereby confirming that

Ratios of K_x/K_z usually fa
but values up to 100 or mor
For consolidated geologic m
erned by the orientation of
other structural conditions,
zontal alignment.

In applying Darcy's law t
media, the appropriate valu
of flow. For directions othe
the K value can be obtaine

$\frac{1}{K_\beta}$

where K_β is the hydraulic
angle β with the horizontal

Groun

From Darcy's law it foll
ment is governed by the h
the hydraulic gradient. To
of natural velocities, assun
= 75 m/day and a hydrauli
from Eq. 3.5

$v = Ki =$

This is approximately equ
strates the sluggish nature

ıyers in Fig. 3.7, the flow
.yer is

(3.30)

ayer. Solving for the head

(3.31)

the other layer so that the

(3.32)

(3.33)

ctivity for the entire system.

(3.34)

(3.35)

(3.36)

ıydraulic conductivity for a

ıtal hydraulic conductivity in
t in the vertical direction. This
ɔove derivations; thus, if

(3.37)

then for the two-layer case from Eqs. 3.28 and 3.35,

$$\frac{K_1 z_1 + K_2 z_2}{z_1 + z_2} > \frac{z_1 + z_2}{\dfrac{z_1}{K_1} + \dfrac{z_2}{K_2}} \tag{3.38}$$

which reduces to[42]

$$\frac{z_1}{z_2}(K_1 - K_2)^2 > 0 \tag{3.39}$$

Because the left side is always positive, it must be greater than zero, thereby confirming that

$$\frac{K_x}{K_z} \geq 1 \tag{3.40}$$

Ratios of K_x/K_z usually fall in the range of 2 to 10 for alluvium,[45] but values up to 100 or more occur where clay layers are present. For consolidated geologic materials, anisotropic conditions are governed by the orientation of strata, fractures, solution openings, or other structural conditions, which do not necessarily possess a horizontal alignment.

In applying Darcy's law to two-dimensional flow in anisotropic media, the appropriate value of K must be selected for the direction of flow. For directions other than horizontal (K_x) and vertical (K_z), the K value can be obtained from

$$\frac{1}{K_\beta} = \frac{\cos^2\beta}{K_x} + \frac{\sin^2\beta}{K_z} \tag{3.41}$$

where K_β is the hydraulic conductivity in the direction making an angle β with the horizontal.

Groundwater Flow Rates

From Darcy's law it follows that the rate of groundwater movement is governed by the hydraulic conductivity of an aquifer and the hydraulic gradient. To obtain an idea of the order of magnitude of natural velocities, assume a productive alluvial aquifer with $K = 75$ m/day and a hydraulic gradient $i = 10$ m/1000 m $= 0.01$. Then from Eq. 3.5

$$v = Ki = 75(0.01) = 0.75 \text{ m/day} \tag{3.42}$$

This is approximately equivalent to 0.5 mm/min, which demonstrates the sluggish nature of natural groundwater movement.

Ground Water and Surface Water
A Single Resource

U.S. Geological Survey Circular 1139

by Thomas C. Winter
Judson W. Harvey
O. Lehn Franke
William M. Alley

Denver, Colorado
1998

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Thomas J. Casadevall, Acting Director

U.S. GOVERNMENT PRINTING OFFICE : 1998

Free on application to the
U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

Library of Congress Cataloging-in-Publications Data

Ground water and surface water : a single resource /
by Thomas C. Winter . . . [et al.].
p. cm. -- (U.S. Geological Survey circular : 1139)
Includes bibliographical references.
1. Hydrology. I. Winter, Thomas C. II. Series.
GB661.2.G76 1998 98–2686
553.7—dc21 CIP
ISBN 0–607–89339–7

FOREWORD

Traditionally, management of water resources has focused on surface water or ground water as if they were separate entities. As development of land and water resources increases, it is apparent that development of either of these resources affects the quantity and quality of the other. Nearly all surface-water features (streams, lakes, reservoirs, wetlands, and estuaries) interact with ground water. These interactions take many forms. In many situations, surface-water bodies gain water and solutes from ground-water systems and in others the surface-water body is a source of ground-water recharge and causes changes in ground-water quality. As a result, withdrawal of water from streams can deplete ground water or conversely, pumpage of ground water can deplete water in streams, lakes, or wetlands. Pollution of surface water can cause degradation of ground-water quality and conversely pollution of ground water can degrade surface water. Thus, effective land and water management requires a clear understanding of the linkages between ground water and surface water as it applies to any given hydrologic setting.

This Circular presents an overview of current understanding of the interaction of ground water and surface water, in terms of both quantity and quality, as applied to a variety of landscapes across the Nation. This Circular is a product of the Ground-Water Resources Program of the U.S. Geological Survey. It serves as a general educational document rather than a report of new scientific findings. Its intent is to help other Federal, State, and local agencies build a firm scientific foundation for policies governing the management and protection of aquifers and watersheds. Effective policies and management practices must be built on a foundation that recognizes that surface water and ground water are simply two manifestations of a single integrated resource. It is our hope that this Circular will contribute to the use of such effective policies and management practices.

(Signed)

Robert M. Hirsch
ChiefHydrologist

CONTENTS

BOXES

PREFACE

- Understanding the interaction of ground water and surface water is essential to water managers and water scientists. Management of one component of the hydrologic system, such as a stream or an aquifer, commonly is only partly effective because each hydrologic component is in continuing interaction with other components. The following are a few examples of common water-resource issues where understanding the interconnections of ground water and surface water is fundamental to development of effective water-resource management and policy.

WATER SUPPLY

- It has become difficult in recent years to construct reservoirs for surface storage of water because of environmental concerns and because of the difficulty in locating suitable sites. An alternative, which can reduce or eliminate the necessity for surface storage, is to use an aquifer system for temporary storage of water. For example, water stored underground during times of high streamflow can be withdrawn during times of low streamflow. The characteristics and extent of the interactions of ground water and surface water affect the success of such conjunctive-use projects.

- Methods of accounting for water rights of streams invariably account for surface-water diversions and surface-water return flows. Increasingly, the diversions from a stream that result from ground-water withdrawals are considered in accounting for water rights as are ground-water return flows from irrigation and other applications of water to the land surface. Accounting for these ground-water components can be difficult and controversial. Another form of water-rights accounting involves the trading of ground-water rights and surface-water rights. This has been proposed as a water-management tool where the rights to the total water resource can be shared. It is an example of the growing realization that ground water and surface water are essentially one resource.

- In some regions, the water released from reservoirs decreases in volume, or is delayed significantly, as it moves downstream because some of the released water seeps into the streambanks. These losses of water and delays in traveltime can be significant, depending on antecedent ground-water and streamflow conditions as well as on other factors such as the condition of the channel and the presence of aquatic and riparian vegetation.

- Storage of water in streambanks, on flood plains, and in wetlands along streams reduces flooding downstream. Modifications of the natural interaction between ground water and surface water along streams, such as drainage of wetlands and construction of levees, can remove some of this natural attenuation of floods. Unfortunately, present knowledge is limited with respect to the effects of land-surface modifications in river valleys on floods and on the natural interaction of ground water and surface water in reducing potential flooding.

WATER QUALITY

- Much of the ground-water contamination in the United States is in shallow aquifers that are directly connected to surface water. In some settings where this is the case, ground water can be a major and potentially long-term contributor to contamination of surface water. Determining the contributions of ground water to contamination of streams and lakes is a critical step in developing effective water-management practices.

- A focus on watershed planning and management is increasing among government agencies responsible for managing water quality as well as broader aspects of the environment. The watershed approach recognizes that water, starting with precipitation, usually moves through the subsurface before entering stream channels and flowing out of the watershed. Integrating ground water into this "systems" approach is essential, but challenging, because of limitations in knowledge of the interactions of ground water and surface water. These difficulties are further complicated by the fact that surface-water watersheds and ground-water watersheds may not coincide.

- To meet water-quality standards and criteria, States and local agencies need to determine the amount of contaminant movement (wasteload) to surface waters so they can issue permits and control discharges of waste. Typically, ground-water inputs are not included in estimates of wasteload; yet, in some cases, water-quality standards and criteria cannot be met without reducing contaminant loads from ground-water discharges to streams.

- It is generally assumed that ground water is safe for consumption without treatment. Concerns about the quality of ground water from wells near streams, where contaminated surface water might be part of the source of water to the well, have led to increasing interest in identifying when filtration or treatment of ground water is needed.

- Wetlands, marshes, and wooded areas along streams (riparian zones) are protected in some areas to help maintain wildlife habitat and the quality of nearby surface water. Greater knowledge of the water-quality functions of riparian zones and of the pathways of exchange between shallow ground water and surface-water bodies is necessary to properly evaluate the effects of riparian zones on water quality.

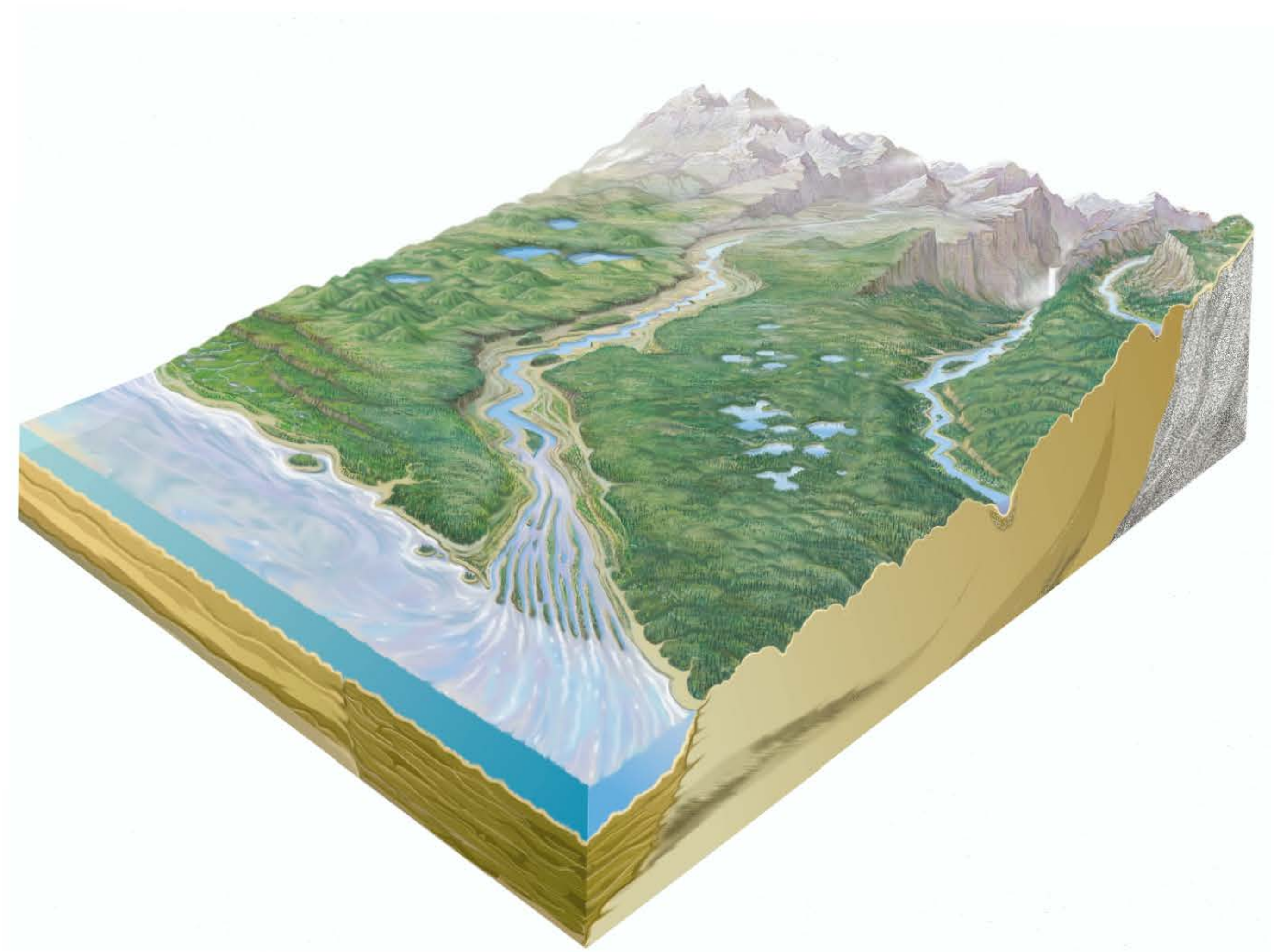
CHARACTERISTICS OF AQUATIC ENVIRONMENTS

- Mixing of ground water with surface water can have major effects on aquatic environments if factors such as acidity, temperature, and dissolved oxygen are altered. Thus, changes in the natural interaction of ground water and surface water caused by human activities can potentially have a significant effect on aquatic environments.

- The flow between surface water and ground water creates a dynamic habitat for aquatic fauna near the interface. These organisms are part of a food chain that sustains a diverse ecological community. Studies indicate that these organisms may provide important indications of water quality as well as of adverse changes in aquatic environments.

- Many wetlands are dependent on a relatively stable influx of ground water throughout changing seasonal and annual weather patterns. Wetlands can be highly sensitive to the effects of ground-water development and to land-use changes that modify the ground-water flow regime of a wetland area. Understanding wetlands in the context of their associated ground-water flow systems is essential to assessing the cumulative effects of wetlands on water quality, ground-water flow, and streamflow in large areas.

- The success of efforts to construct new wetlands that replicate those that have been destroyed depends on the extent to which the replacement wetland is hydrologically similar to the destroyed wetland. For example, the replacement of a wetland that is dependent on ground water for its water and chemical input needs to be located in a similar ground-water discharge area if the new wetland is to replicate the original. Although a replacement wetland may have a water depth similar to the original, the communities that populate the replacement wetland may be completely different from communities that were present in the original wetland because of differences in hydrogeologic setting.



Ground Water and Surface Water
A Single Resource

by T.C. Winter
J.W. Harvey
O.L. Franke
W.M. Alley

INTRODUCTION

As the Nation's concerns over water resources and the environment increase, the importance of considering ground water and surface water as a single resource has become increasingly evident. Issues related to water supply, water quality, and degradation of aquatic environments are reported on frequently. The interaction of ground water and surface water has been shown to be a significant concern in many of these issues. For example, contaminated aquifers that discharge to streams can result in long-term contamination of surface water; conversely, streams can be a major source of contamination to aquifers. Surface water commonly is hydraulically connected to ground water, but the interactions are difficult to observe and measure and commonly have been ignored in water-management considerations and policies. Many natural processes and human activities affect the interactions of ground water and surface water. The purpose of this report is to present our current understanding of these processes and activities as well as limitations in our knowledge and ability to characterize them.

"Surface water commonly is hydraulically connected to ground water, but the interactions are difficult to observe and measure"

NATURAL PROCESSES OF GROUND-WATER AND SURFACE-WATER INTERACTION

The Hydrologic Cycle and Interactions of Ground Water and Surface Water

The hydrologic cycle describes the continuous movement of water above, on, and below the surface of the Earth. The water on the Earth's surface—surface water—occurs as streams, lakes, and wetlands, as well as bays and oceans. Surface water also includes the solid forms of water—snow and ice. The water below the surface of the Earth primarily is ground water, but it also includes soil water.

The hydrologic cycle commonly is portrayed by a very simplified diagram that shows only major transfers of water between continents and oceans, as in Figure 1. However, for understanding hydrologic processes and managing water resources, the hydrologic cycle needs to be viewed at a wide range of scales and as having a great deal of variability in time and space. Precipitation, which is the source of virtually all freshwater in the hydrologic cycle, falls nearly everywhere, but its distribution is highly variable. Similarly, evaporation and transpiration return water to the atmosphere nearly everywhere, but evaporation and transpiration rates vary considerably according to climatic conditions. As a result, much of the precipitation never reaches the oceans as surface and subsurface runoff before the water is returned to the atmosphere. The relative magnitudes of the individual components of the hydrologic cycle, such as evapotranspiration, may differ significantly even at small scales, as between an agricultural field and a nearby woodland.

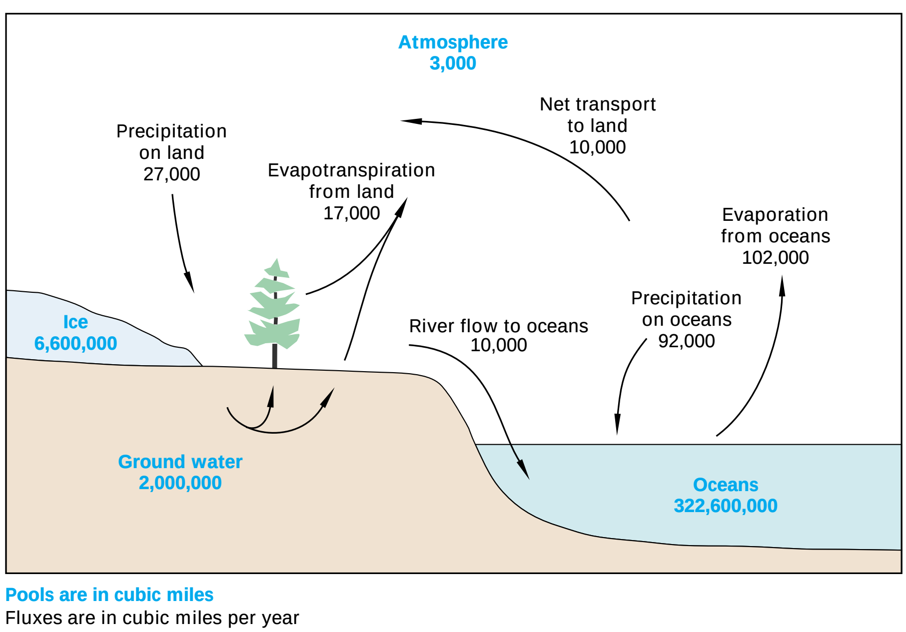


Figure 1. Ground water is the second smallest of the four main pools of water on Earth, and river flow to the oceans is one of the smallest fluxes, yet ground water and surface water are the components of the hydrologic system that humans use most. (Modified from Schelesinger, W.H., 1991, Biogeochemistry–An analysis of global change: Academic Press, San Diego, California.) (Used with permission.)

To present the concepts and many facets of the interaction of ground water and surface water in a unified way, a conceptual landscape is used (Figure 2). The conceptual landscape shows in a very general and simplified way the interaction of ground water with all types of surface water, such as streams, lakes, and wetlands, in many different terrains from the mountains to the oceans. The intent of Figure 2 is to emphasize that ground water and surface water interact at many places throughout the landscape.

Movement of water in the atmosphere and on the land surface is relatively easy to visualize, but the movement of ground water is not. Concepts related to ground water and the movement of ground water are introduced in Box A. As illustrated in Figure 3, ground water moves along flow paths of varying lengths from areas of recharge to areas of discharge. The generalized flow paths in Figure 3 start at the water table, continue through the ground-water system, and terminate at the stream or at the pumped well. The source of water to the water table (ground-water recharge) is infiltration of precipitation through the unsaturated zone. In the uppermost, unconfined aquifer, flow paths near the stream can be tens to hundreds of feet in length and have corresponding traveltimes of days to a few years. The longest and deepest flow paths in Figure 3 may be thousands of feet to tens of miles in length, and traveltimes may range from decades to millennia. In general, shallow ground water is more susceptible to contamination from human sources and activities because of its close proximity to the land surface. Therefore, shallow, local patterns of ground-water flow near surface water are emphasized in this Circular.

"Ground water moves along flow paths of varying lengths in transmitting water from areas of recharge to areas of discharge"

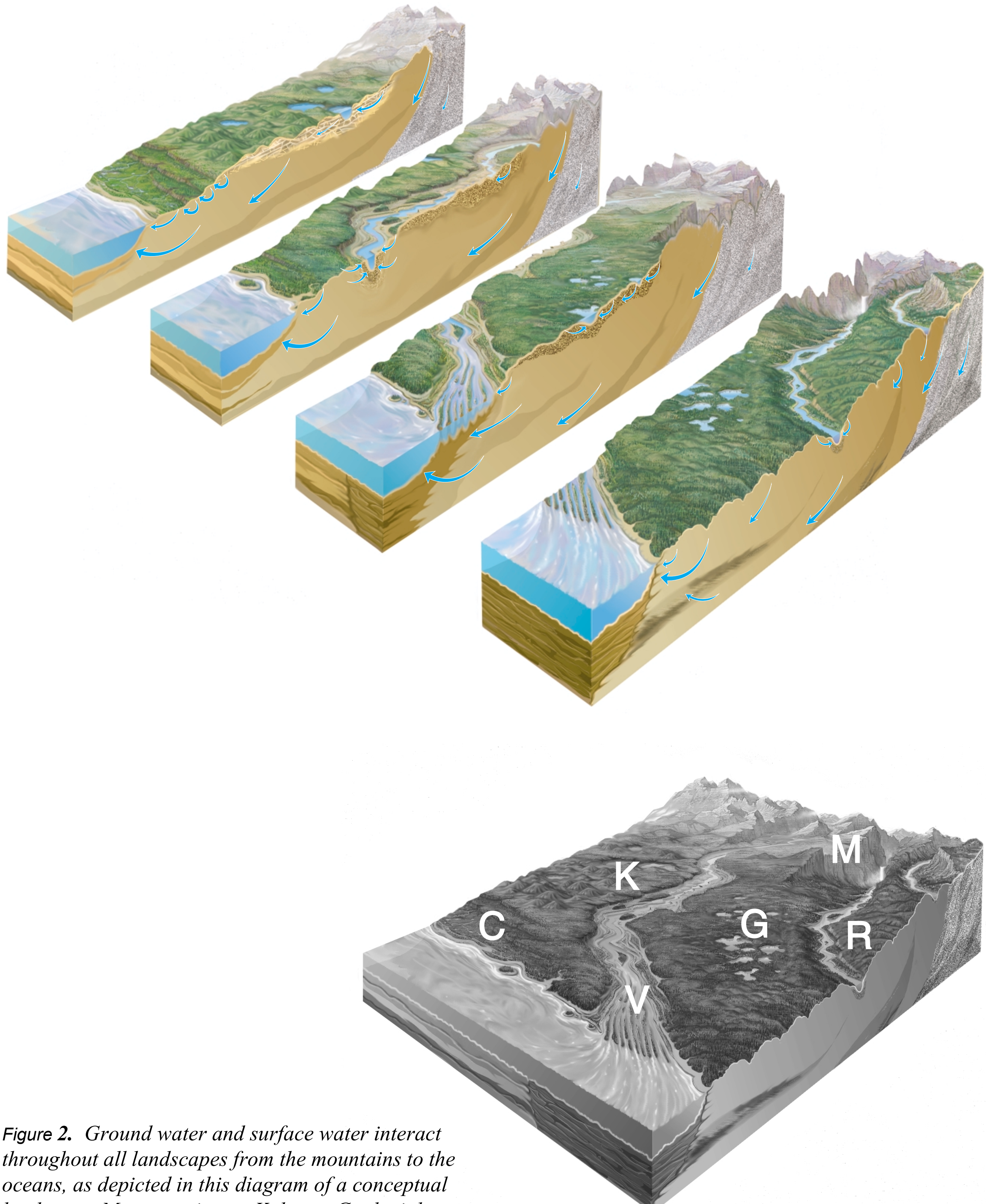


Figure 2. *Ground water and surface water interact throughout all landscapes from the mountains to the oceans, as depicted in this diagram of a conceptual landscape. M, mountainous; K, karst; G, glacial; R, riverine (small); V, riverine (large); C, coastal.*

Small-scale geologic features in beds of surface-water bodies affect seepage patterns at scales too small to be shown in Figure 3. For example, the size, shape, and orientation of the sediment grains in surface-water beds affect seepage patterns. If a surface-water bed consists of one sediment type, such as sand, inflow seepage is greatest at the shoreline, and it decreases in a nonlinear pattern away from the shoreline (Figure 4). Geologic units having different permeabilities also affect seepage distribution in surface-water beds. For example, a highly permeable sand layer within a surface-water bed consisting largely of silt will transmit water preferentially into the surface water as a spring (Figure 5).

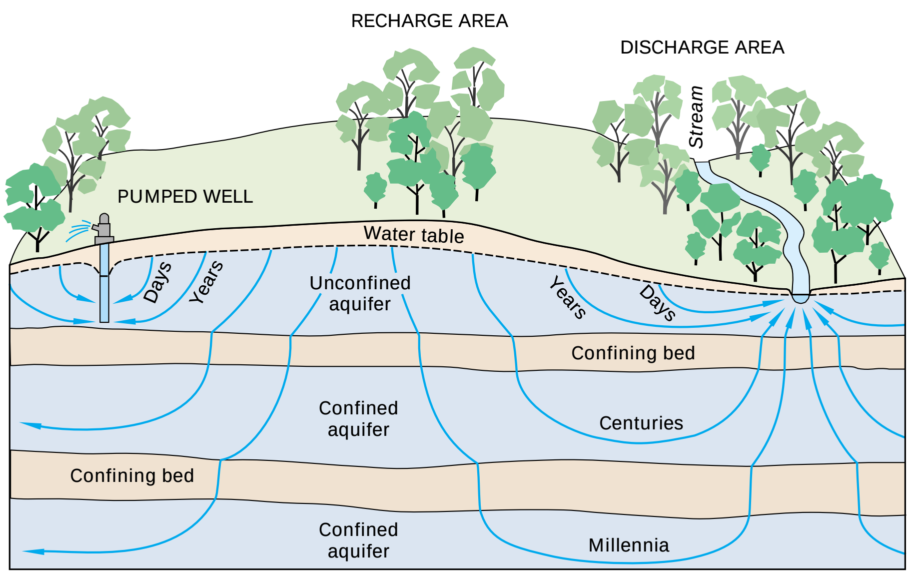


Figure 3. Ground-water flow paths vary greatly in length, depth, and traveltime from points of recharge to points of discharge in the ground-water system.

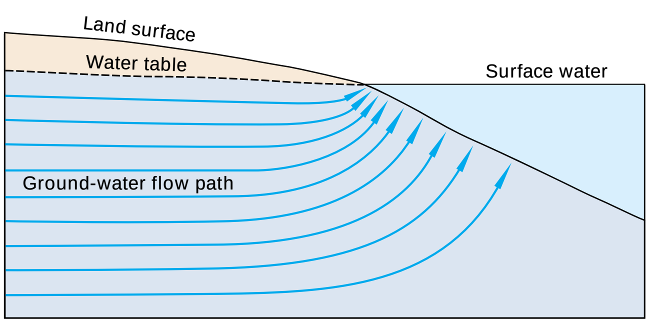


Figure 4. Ground-water seepage into surface water usually is greatest near shore. In flow diagrams such as that shown here, the quantity of discharge is equal between any two flow lines; therefore, the closer flow lines indicate greater discharge per unit of bottom area.

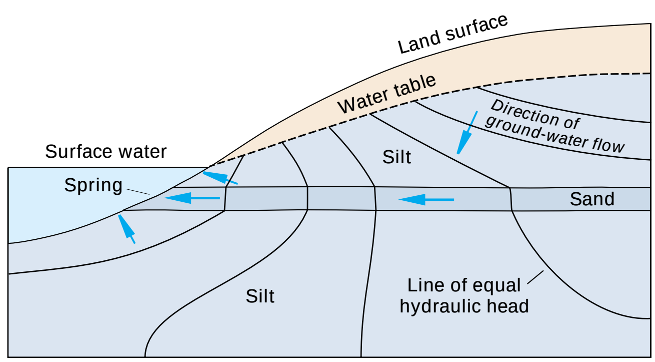


Figure 5. Subaqueous springs can result from preferred paths of ground-water flow through highly permeable sediments.

A

Concepts of Ground Water, Water Table, and Flow Systems

SUBSURFACE WATER

Water beneath the land surface occurs in two principal zones, the unsaturated zone and the saturated zone (Figure A–1). In the unsaturated zone, the voids—that is, the spaces between grains of gravel, sand, silt, clay, and cracks within rocks—contain both air and water. Although a considerable amount of water can be present in the unsaturated zone, this water cannot be pumped by wells because it is held too tightly by capillary forces. The upper part of the unsaturated zone is the soil-water zone. The soil zone is crisscrossed by roots, voids left by decayed roots, and animal and worm burrows, which enhance the infiltration of precipitation into the soil zone. Soil water is used by plants in life functions and transpiration, but it also can evaporate directly to the atmosphere.

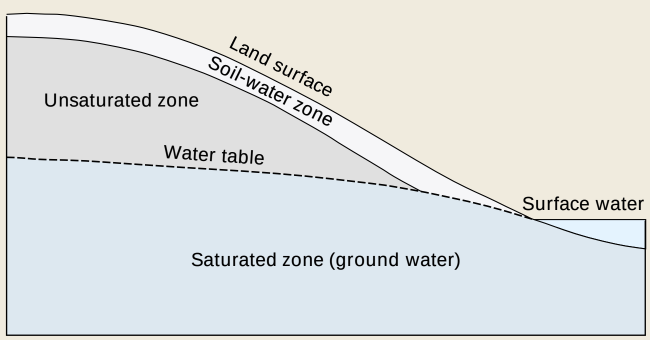


Figure A–1. The water table is the upper surface of the saturated zone. The water table meets surface-water bodies at or near the shoreline of surface water if the surface-water body is connected to the ground-water system.

In contrast to the unsaturated zone, the voids in the saturated zone are completely filled with water. Water in the saturated zone is referred to as ground water. The upper surface of the saturated zone is referred to as the water table. Below the water table, the water pressure is great enough to allow water to enter wells, thus permitting ground water to be withdrawn for use. A well is constructed by inserting a pipe into a drilled hole; a screen is attached, generally at its base, to prevent earth materials from entering the pipe along with the water pumped through the screen.

The depth to the water table is highly variable and can range from zero, when it is at land surface, to hundreds or even thousands of feet in some types of landscapes. Usually, the depth to the water table is small near permanent bodies of surface water such as streams, lakes, and wetlands. An important characteristic of the water table is that its configuration varies seasonally and from year to year because ground-water recharge, which is the accretion of water to the upper surface of the saturated zone, is related to the wide variation in the quantity, distribution, and timing of precipitation.

THE WATER TABLE

The depth to the water table can be determined by installing wells that penetrate the top of the saturated zone just far enough to hold standing water. Preparation of a water-table map requires that only wells that have their well screens placed near the water table be used. If the depth to water is measured at a number of such wells throughout an area of study, and if those water levels are referenced to a common datum such as sea level, the data can be contoured to indicate the configuration of the water table (Figure A–2).

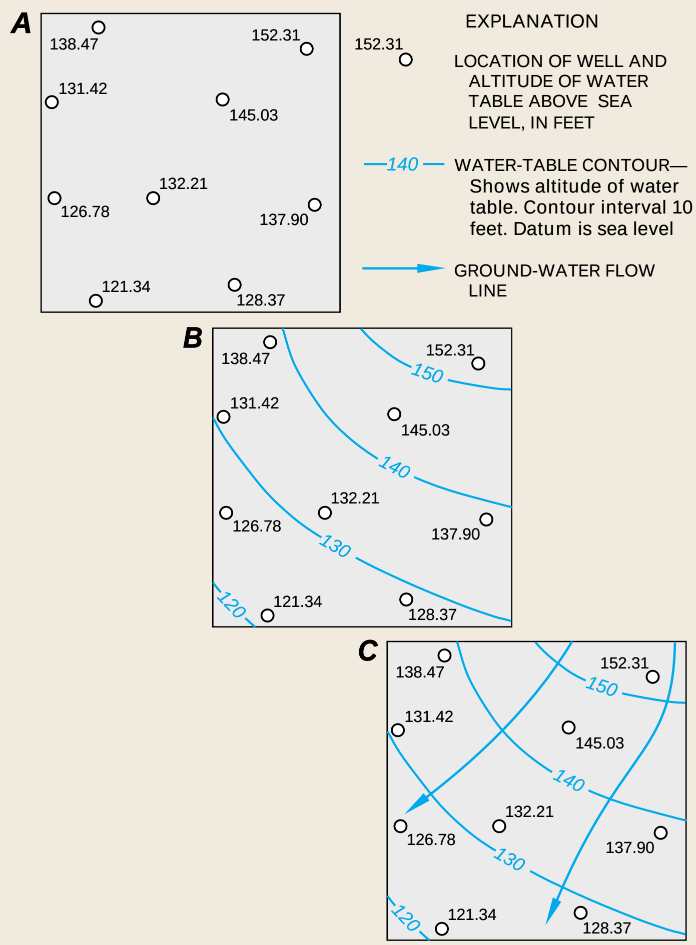


Figure A–2. Using known altitudes of the water table at individual wells (A), contour maps of the water-table surface can be drawn (B), and directions of ground-water flow along the water table can be determined (C) because flow usually is approximately perpendicular to the contours.

In addition to various practical uses of a water-table map, such as estimating an approximate depth for a proposed well, the configuration of the water table provides an indication of the approximate direction of ground-water flow at any location on the water table. Lines drawn perpendicular to water-table contours usually indicate the direction of ground-water flow along the upper surface of the ground-water system. The water table is continually adjusting to changing recharge and discharge patterns. Therefore, to construct a water-table map, water-level measurements must be made at approximately the same time, and the resulting map is representative only of that specific time.

GROUND-WATER MOVEMENT

The ground-water system as a whole is actually a three-dimensional flow field; therefore, it is important to understand how the vertical components of ground-water movement affect the interaction of ground water and surface water. A vertical section of a flow field indicates how potential energy is distributed beneath the water table in the ground-water system and how the energy distribution can be used to determine vertical components of flow near a surface-water body. The term hydraulic head, which is the sum of elevation and water pressure divided by the weight density of water, is used to describe potential energy in ground-water flow systems. For example, Figure A–3 shows a generalized vertical section of subsurface water flow. Water that infiltrates at land surface moves vertically downward to the water table to become ground water. The ground water then moves both vertically and laterally within the ground-water system. Movement is downward and lateral on the right side of the diagram, mostly lateral in the center, and lateral and upward on the left side of the diagram.

Flow fields such as these can be mapped in a process similar to preparing water-table maps, except that vertically distributed piezometers need to be used instead of water-table wells. A piezometer is a well that has a very short screen so the water level represents hydraulic head in only a very small part of the ground-water system. A group of piezometers completed at different depths at the same location is referred to as a piezometer nest. Three such piezometer nests are shown in Figure A–3 (locations A, B, and C). By starting at a water-table contour, and using the water-level data from the piezometer nests, lines of equal hydraulic head can be drawn. Similar to drawing flow direction on water-table maps, flow lines can be drawn approximately perpendicular to these lines of equal hydraulic head, as shown in Figure A–3.

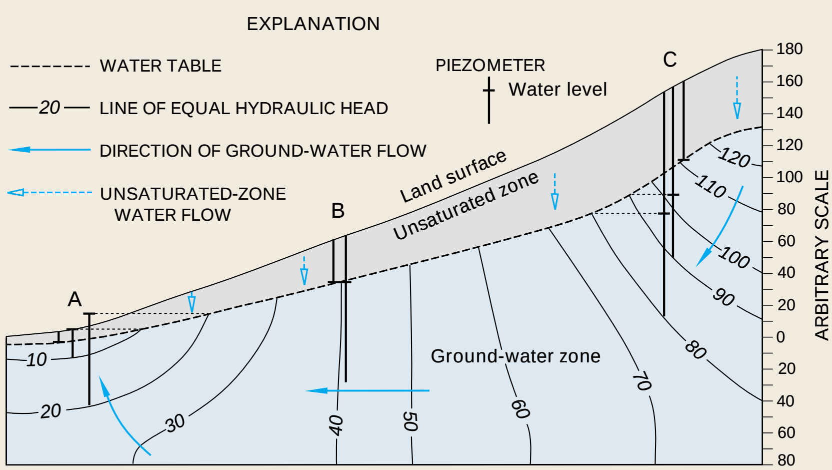


Figure A–3. If the distribution of hydraulic head in vertical section is known from nested piezometer data, zones of downward, lateral, and upward components of ground-water flow can be determined.

Actual flow fields generally are much more complex than that shown in Figure A–3. For example, flow systems of different sizes and depths can be present, and they can overlie one another, as indicated in Figure A–4. In a local flow system, water that recharges at a water-table high discharges to an adjacent lowland. Local flow systems are the most dynamic and the shallowest flow systems; therefore, they have the greatest interchange with surface water. Local flow systems can be underlain by intermediate and regional flow systems. Water in deeper flow systems have longer flow paths and longer contact time with subsurface materials; therefore, the water generally contains more dissolved chemicals. Nevertheless, these deeper flow systems also eventually discharge to surface water, and they can have a great effect on the chemical characteristics of the receiving surface water.

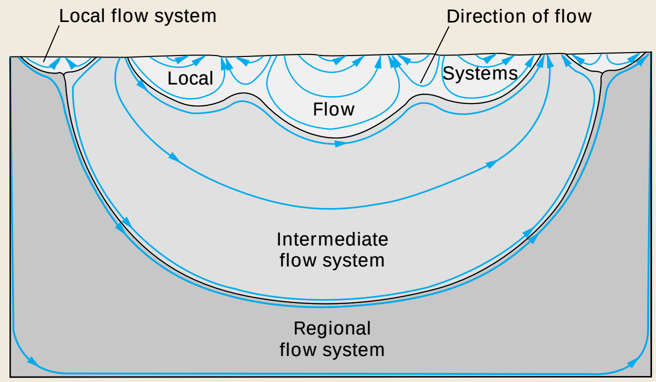


Figure A–4. Ground-water flow systems can be local, intermediate, and regional in scale. Much ground-water discharge into surface-water bodies is from local flow systems. (Figure modified from Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: p. 75–96 in Proceedings of Hydrology Symposium No. 3, Groundwater, Queen's Printer, Ottawa, Canada.)

GROUND-WATER DISCHARGE

The quantity of ground-water discharge (flux) to and from surface-water bodies can be determined for a known cross section of aquifer by multiplying the hydraulic gradient, which is determined from the hydraulic-head measurements in wells and piezometers, by the permeability of the aquifer materials. Permeability is a quantitative measure of the ease of water movement through aquifer materials. For example, sand is more permeable than clay because the pore spaces between sand grains are larger than pore spaces between clay particles.

Changing meteorological conditions also strongly affect seepage patterns in surface-water beds, especially near the shoreline. The water table commonly intersects land surface at the shoreline, resulting in no unsaturated zone at this point. Infiltrating precipitation passes rapidly through a thin unsaturated zone adjacent to the shoreline, which causes water-table mounds to form quickly adjacent to the surface water (Figure 6). This process, termed focused recharge, can result in increased ground-water inflow to surface-water bodies, or it can cause inflow to surface-water bodies that normally have seepage to ground water. Each precipitation event has the potential to cause this highly transient flow condition near shorelines as well as at depressions in uplands (Figure 6).

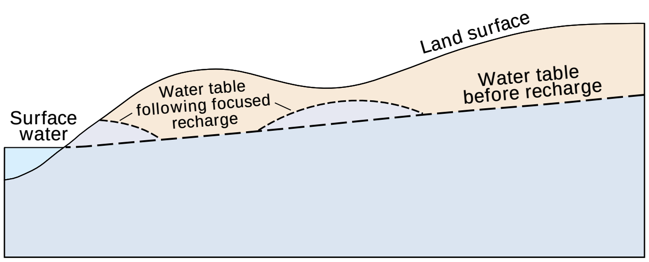


Figure 6. Ground-water recharge commonly is focused initially where the unsaturated zone is relatively thin at the edges of surface-water bodies and beneath depressions in the land surface.

Transpiration by nearshore plants has the opposite effect of focused recharge. Again, because the water table is near land surface at edges of surface-water bodies, plant roots can penetrate into the saturated zone, allowing the plants to transpire water directly from the ground-water system (Figure 7). Transpiration of ground water commonly results in a drawdown of the water table much like the effect of a pumped well. This highly variable daily and seasonal transpiration of ground water may significantly reduce ground-water discharge to a surface-water body or even cause movement of surface water into the subsurface. In many places it is possible to measure diurnal changes in the direction of flow during seasons of active plant growth; that is, ground water moves into the surface water during the night, and surface water moves into shallow ground water during the day.

These periodic changes in the direction of flow also take place on longer time scales: focused recharge from precipitation predominates during wet periods and drawdown by transpiration predominates during dry periods. As a result, the two processes, together with the geologic controls on seepage distribution, can cause flow conditions at the edges of surface-water bodies to be extremely variable. These "edge effects" probably affect small surface-water bodies more than large surface-water bodies because the ratio of edge length to total volume is greater for small water bodies than it is for large ones.

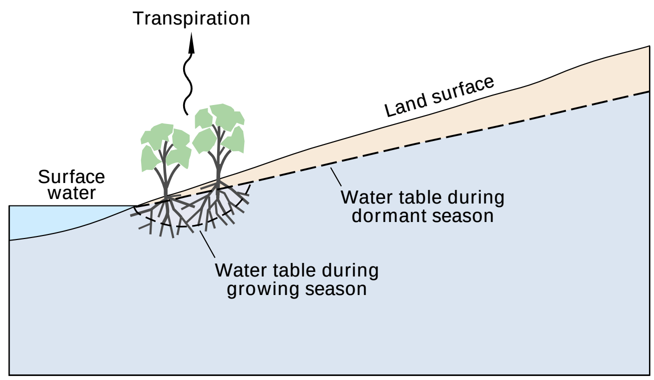


Figure 7. Where the depth to the water table is small adjacent to surface-water bodies, transpiration directly from ground water can cause cones of depression similar to those caused by pumping wells. This sometimes draws water directly from the surface water into the subsurface.

INTERACTION OF GROUND WATER AND STREAMS

Streams interact with ground water in all types of landscapes (see Box B). The interaction takes place in three basic ways: streams gain water from inflow of ground water through the streambed (gaining stream, Figure 8*A*), they lose water to ground water by outflow through the streambed (losing stream, Figure 9*A*), or they do both, gaining in some reaches and losing in other reaches. For ground water to discharge into a stream channel, the altitude of the water table in the vicinity of the stream must be higher than the altitude of the stream-water surface. Conversely, for surface water to seep to ground water, the altitude of the water table in the vicinity of the stream must be lower than the altitude of the stream-water surface. Contours of water-table elevation indicate gaining streams by pointing in an upstream direction (Figure 8*B*), and they indicate losing streams by pointing in a downstream direction (Figure 9*B*) in the immediate vicinity of the stream.

Losing streams can be connected to the ground-water system by a continuous saturated zone (Figure 9*A*) or can be disconnected from

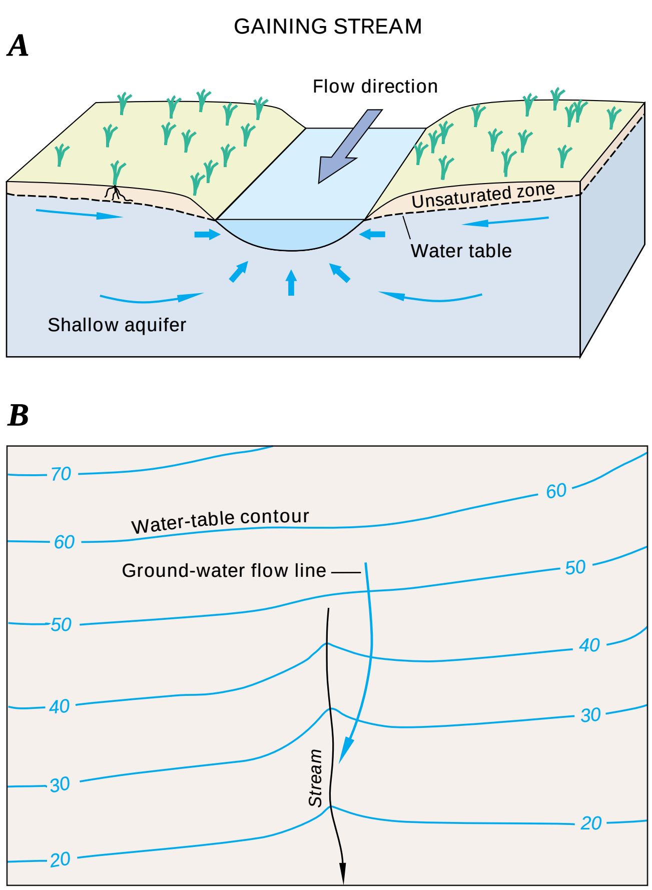


Figure 8. Gaining streams receive water from the ground-water system (A). This can be determined from water-table contour maps because the contour lines point in the upstream direction where they cross the stream (B).

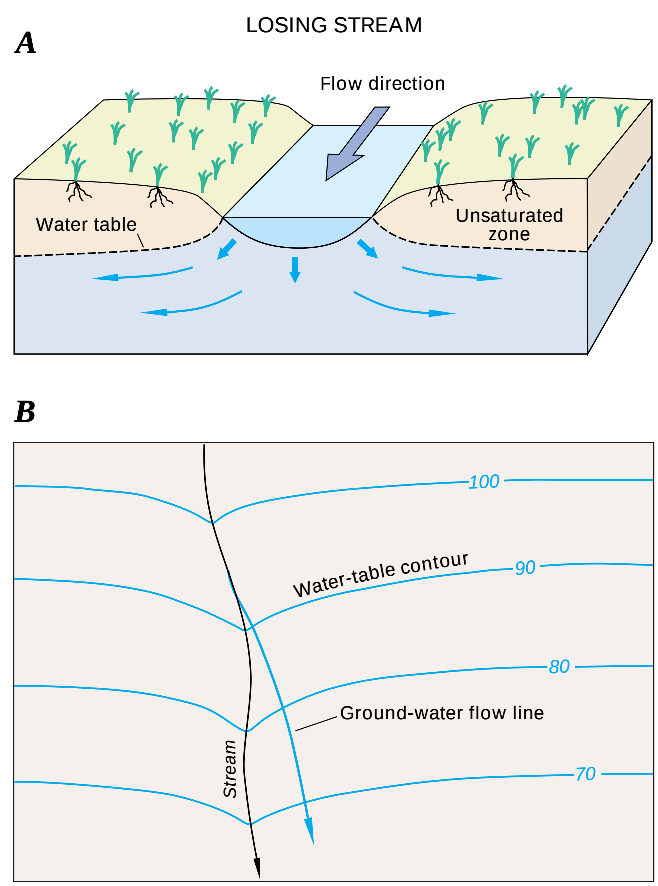


Figure 9. Losing streams lose water to the ground-water system (A). This can be determined from water-table contour maps because the contour lines point in the downstream direction where they cross the stream (B).

the ground-water system by an unsaturated zone. Where the stream is disconnected from the ground-water system by an unsaturated zone, the water table may have a discernible mound below the stream (Figure 10) if the rate of recharge through the streambed and unsaturated zone is greater than the rate of lateral ground-water flow away from the water-table mound. An important feature of streams that are disconnected from ground water is that pumping of shallow ground water near the stream does not affect the flow of the stream near the pumped wells.

In some environments, streamflow gain or loss can persist; that is, a stream might always gain water from ground water, or it might always lose water to ground water. However, in other environments, flow direction can vary a great deal along a stream; some reaches receive ground water, and other reaches lose water to ground water. Furthermore, flow direction can change in very short timeframes as a result of individual storms causing focused recharge near the streambank, temporary flood peaks moving down the channel, or transpiration of ground water by streamside vegetation.

A type of interaction between ground water and streams that takes place in nearly all streams at one time or another is a rapid rise in stream stage that causes water to move from the stream into the streambanks. This process, termed bank storage (Figures 11 and 12*B*), usually is caused by storm precipitation, rapid snowmelt, or release of water

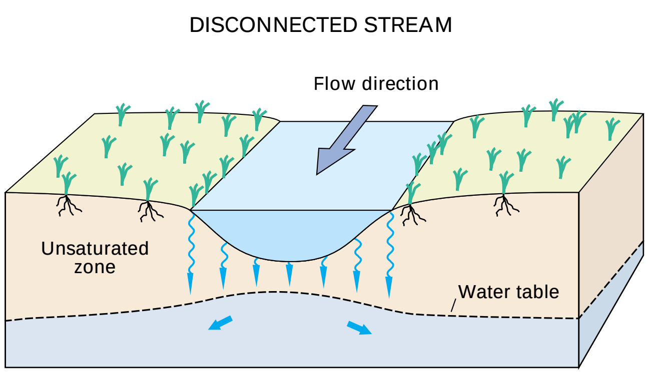


Figure ***10****.* *Disconnected streams are separated from the ground-water system by an unsaturated zone.*

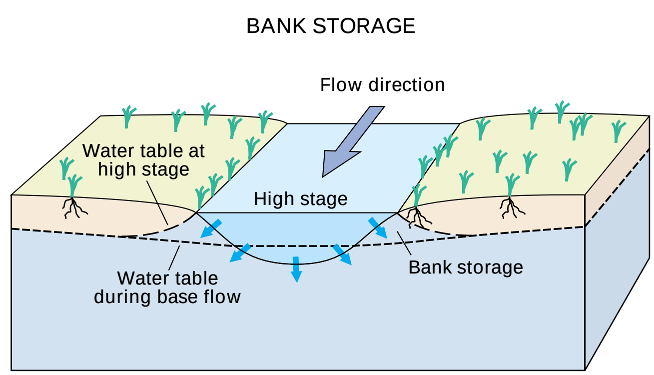


Figure ***11****.* *If stream levels rise higher than adjacent ground-water levels, stream water moves into the streambanks as bank storage.*

"Streams interact with ground water in three basic ways: streams gain water from inflow of ground water through the streambed (gaining stream), they lose water to ground water by outflow through the streambed (losing stream), or they do both, gaining in some reaches and losing in other reaches"

from a reservoir upstream. As long as the rise in stage does not overtop the streambanks, most of the volume of stream water that enters the streambanks returns to the stream within a few days or weeks. The loss of stream water to bank storage and return of this water to the stream in a period of days or weeks tends to reduce flood peaks and later supplement stream flows. If the rise in stream stage is sufficient to overtop the banks and flood large areas of the land surface, widespread recharge to the water table can take place throughout the flooded area (Figure 12*C*). In this case, the time it takes for the recharged floodwater to return to the stream by ground-water flow may be weeks, months, or years because the lengths of the ground-water flow paths are much longer than those resulting from local bank storage. Depending on the frequency, magnitude, and intensity of storms and on the related magnitude of increases in stream stage, some streams and adjacent shallow aquifers may be in a continuous readjustment from interactions related to bank storage and overbank flooding.

In addition to bank storage, other processes may affect the local exchange of water between streams and adjacent shallow aquifers. Changes in streamflow between gaining and losing conditions can also be caused by pumping ground water near streams (see Box C). Pumping can intercept ground water that would otherwise have discharged to a gaining stream, or at higher pumping rates it can induce flow from the stream to the aquifer.

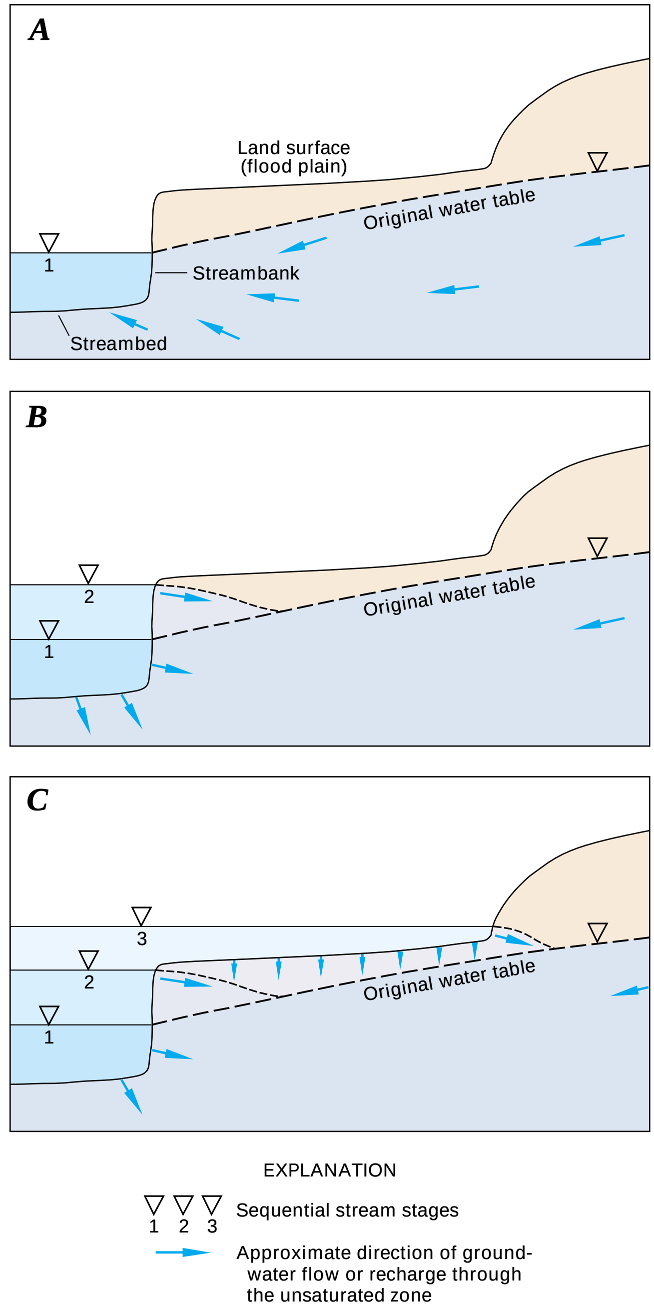


Figure 12. *If stream levels rise higher than their streambanks (C), the floodwaters recharge ground water throughout the flooded areas.*

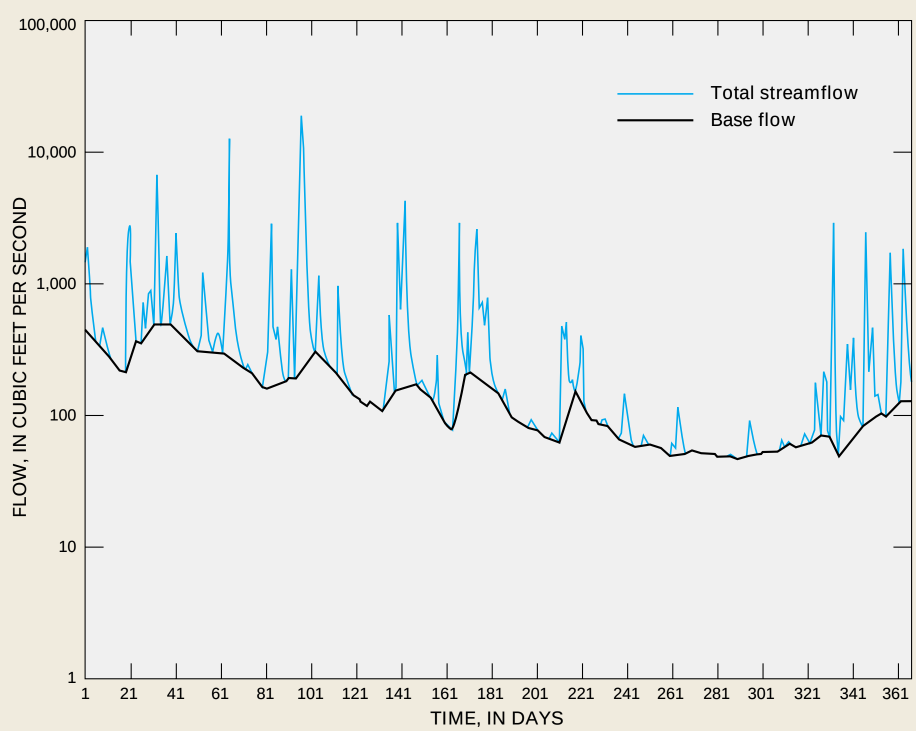
B

The Ground-Water Component of Streamflow

Ground water contributes to streams in most physiographic and climatic settings. Even in settings where streams are primarily losing water to ground water, certain reaches may receive ground-water inflow during some seasons. The proportion of stream water that is derived from ground-water inflow varies across physiographic and climatic settings. The amount of water that ground water contributes to streams can be estimated by analyzing streamflow hydrographs to determine the ground-water component, which is termed base flow (Figure B–1). Several different methods of analyzing hydrographs have been used by hydrologists to determine the base-flow component of streamflow.

One of the methods, which provides a conservative estimate of base flow, was used to determine the ground-water contribution to streamflow in 24 regions in the conterminous United States. The regions, delineated on the basis of physiography and climate, are believed to have common characteristics with respect to the interactions of ground water and surface water (Figure B–2). Fifty-four streams were selected for the analysis, at least two in each of the 24 regions. Streams were selected that had drainage basins less than 250 square miles and that had less than 3 percent of the drainage area covered by lakes and wetlands. Daily streamflow values for the 30-year period, 1961–1990, were used for the analysis of each stream. The analysis indicated that, for the 54 streams over the 30-year period, an average of 52 percent of the streamflow was contributed by ground water. Ground-water contributions ranged from 14 percent to 90 percent, and the median was 55 percent. The ground-water contribution to streamflow for selected streams can be compared in Figure B–2. As an example of the effect that geologic setting has on the contribution of ground water to streamflow, the Forest River in North Dakota can be compared to the Sturgeon River in Michigan. The Forest River Basin is underlain by poorly permeable silt and clay deposits, and only about 14 percent of its average annual flow is contributed by ground water; in contrast, the Sturgeon River Basin is underlain by highly permeable sand and gravel, and about 90 percent of its average annual flow is contributed by ground water.

Figure B–1. The ground-water component of streamflow was estimated from a streamflow hydrograph for the Homochitto River in Mississippi, using a method developed by the institute of Hydrology, United Kingdom. (Institute of Hydrology, 1980, Low flow studies: Wallingford, Oxon, United Kingdom, Research Report No. 1.)



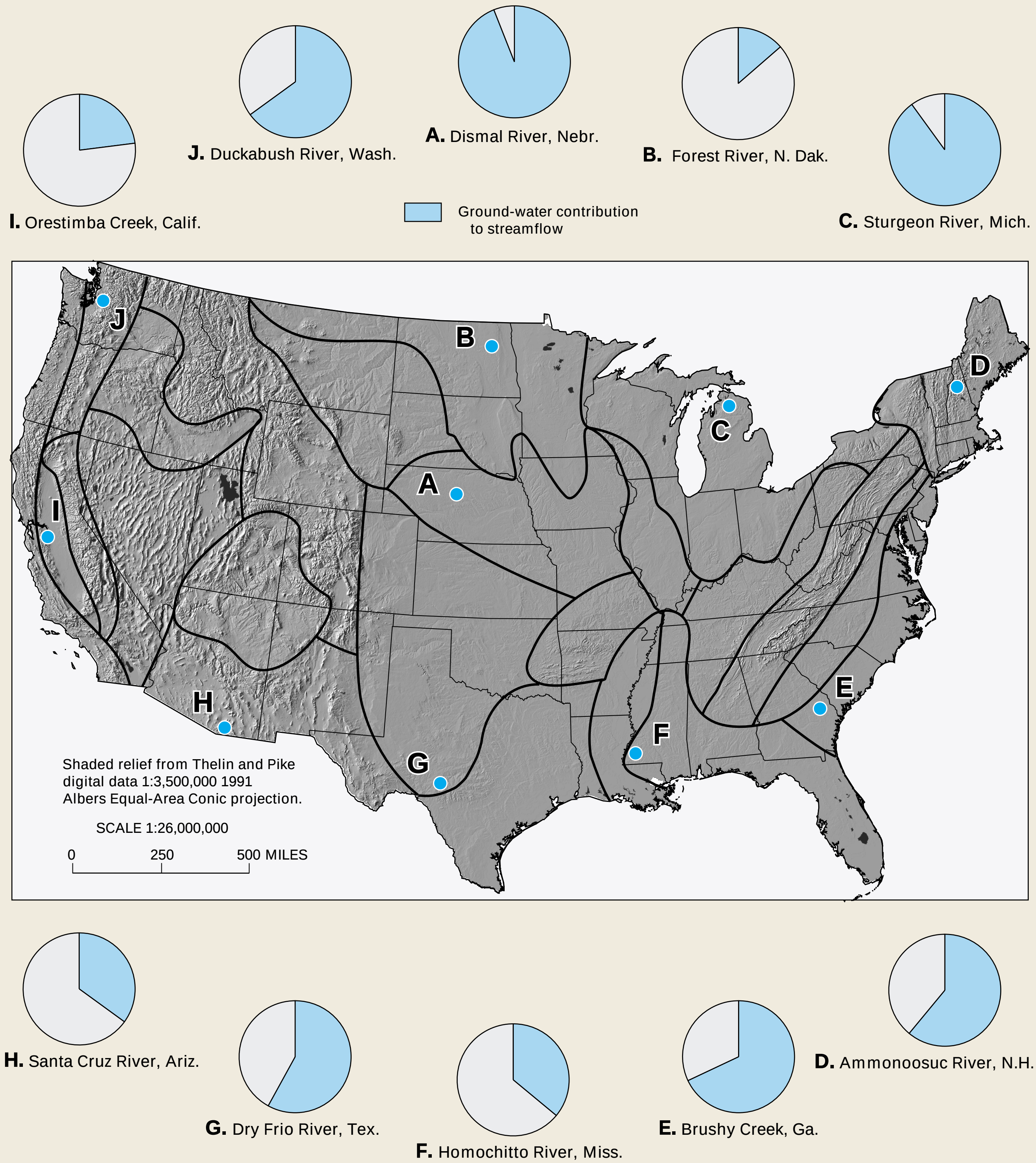


Figure B–2. In the conterminous United States, 24 regions were delineated where the interactions of ground water and surface water are considered to have similar characteristics. The estimated ground-water contribution to streamflow is shown for specific streams in 10 of the regions.

C

The Effect of Ground-Water Withdrawals on Surface Water

Withdrawing water from shallow aquifers that are directly connected to surface-water bodies can have a significant effect on the movement of water between these two water bodies. The effects of pumping a single well or a small group of wells on the hydrologic regime are local in scale. However, the effects of many wells withdrawing water from an aquifer over large areas may be regional in scale.

Withdrawing water from shallow aquifers for public and domestic water supply, irrigation, and industrial uses is widespread. Withdrawing water from shallow aquifers near surface-water bodies can diminish the available surface-water supply by capturing some of the ground-water flow that otherwise would have discharged to surface water or by inducing flow from surface water into the surrounding aquifer system. An analysis of the sources of water to a pumping well in a shallow aquifer that discharges to a stream is provided here to gain insight into how a pumping well can change the quantity and direction of flow between the shallow aquifer and the stream. Furthermore, changes in the direction of flow between the two water bodies can affect transport of contaminants associated with the moving water. Although a stream is used in the example, the results apply to all surface-water bodies, including lakes and wetlands.

A ground-water system under predevelopment conditions is in a state of dynamic equilibrium—for example, recharge at the water table is equal to ground-water discharge to a stream (Figure C–1*A*). Assume a well is installed and is pumped continually at a rate, Q_1. After a new state of dynamic equilibrium is achieved, inflow to the ground-water system from recharge will equal outflow to the stream plus the withdrawal from the well. In this new equilibrium, some of the ground water that would have discharged to the stream is intercepted by the well, and a ground-water divide, which is a line separating directions of flow, is established locally between the well and the stream (Figure C–1*B*). If the well is pumped at a higher rate, Q_2, at a later time a new equilibrium is reached. Under this condition, the ground-water divide between the well and the stream is no longer present and withdrawals from the well induce movement of water from the stream into the aquifer (Figure C–1*C*). Thus, pumpage reverses the hydrologic condition of the stream in this reach from a ground-water discharge feature to a ground-water recharge feature.

In the hydrologic system depicted in Figures C–1*A* and C–1*B*, the quality of the stream water generally will have little effect on the quality of the shallow ground water. However, in the case of the well pumping at the higher rate, Q_2 (Figure C–1*C*), the quality of the stream water, which locally recharges the shallow aquifer, can affect the quality of ground water between the well and the stream as well as the quality of the ground water withdrawn from the well.

This hypothetical withdrawal of water from a shallow aquifer that discharges to a nearby surface-water body is a simplified but compelling illustration of the concept that ground water and surface water are one resource. In the long term, the quantity of ground water withdrawn is approximately equal to the reduction in streamflow that is potentially available to downstream users.

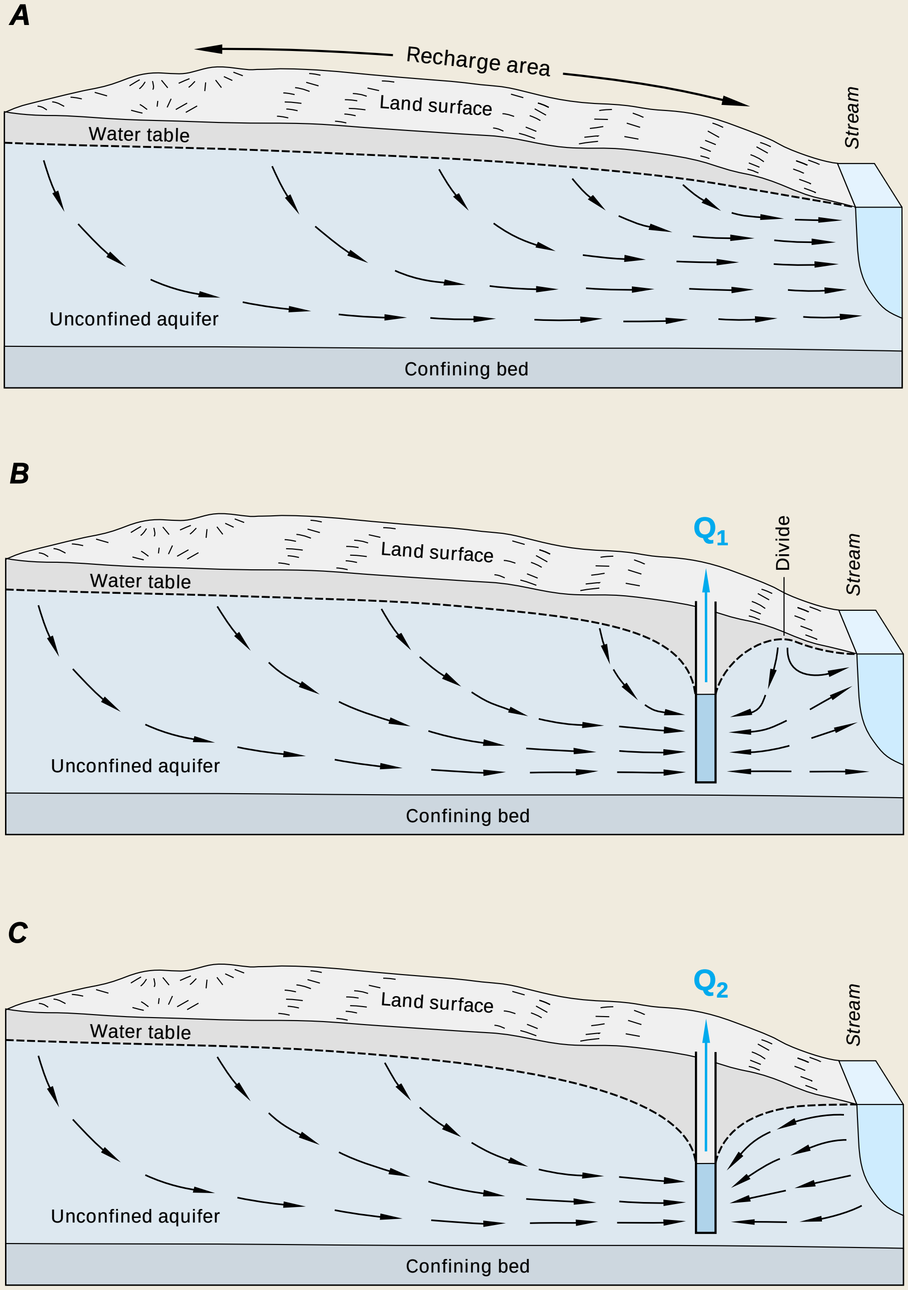


Figure C–1. In a schematic hydrologic setting where ground water discharges to a stream under natural conditions (A), placement of a well pumping at a rate (Q_1) near the stream will intercept part of the ground water that would have discharged to the stream (B). If the well is pumped at an even greater rate (Q_2), it can intercept additional water that would have discharged to the stream in the vicinity of the well and can draw water from the stream to the well (C).

Where streamflow is generated in headwaters areas, the changes in streamflow between gaining and losing conditions may be particularly variable (Figure 13). The headwaters segment of streams can be completely dry except during storm events or during certain seasons of the year when snowmelt or precipitation is sufficient to maintain continuous flow for days or weeks. During these times, the stream will lose water to the unsaturated zone beneath its bed. However, as the water table rises through recharge in the headwaters area, the losing reach may become a gaining reach as the water table rises above the level of the stream. Under these conditions, the point where ground water first contributes to the stream gradually moves upstream.

Some gaining streams have reaches that lose water to the aquifer under normal conditions of streamflow. The direction of seepage through the bed of these streams commonly is related to abrupt changes in the slope of the streambed (Figure 14*A*) or to meanders in the stream channel (Figure 14*B*). For example, a losing stream reach usually is located at the downstream end of pools in pool and riffle streams (Figure 14*A*), or upstream from channel bends in meandering streams (Figure 14*B*). The subsurface zone where stream water flows through short segments of its adjacent bed and banks is referred to as the hyporheic zone. The size and geometry of hyporheic zones surrounding streams vary greatly in time and space. Because of mixing between ground water and surface water in the hyporheic zone, the chemical and biological character of the hyporheic zone may differ markedly from adjacent surface water and ground water.

Ground-water systems that discharge to streams can underlie extensive areas of the land surface (Figure 15). As a result, environmental conditions at the interface between ground water and surface water reflect changes in the broader landscape. For example, the types and numbers of organisms in a given reach of streambed result, in part, from interactions between water in the hyporheic zone and ground water from distant sources.

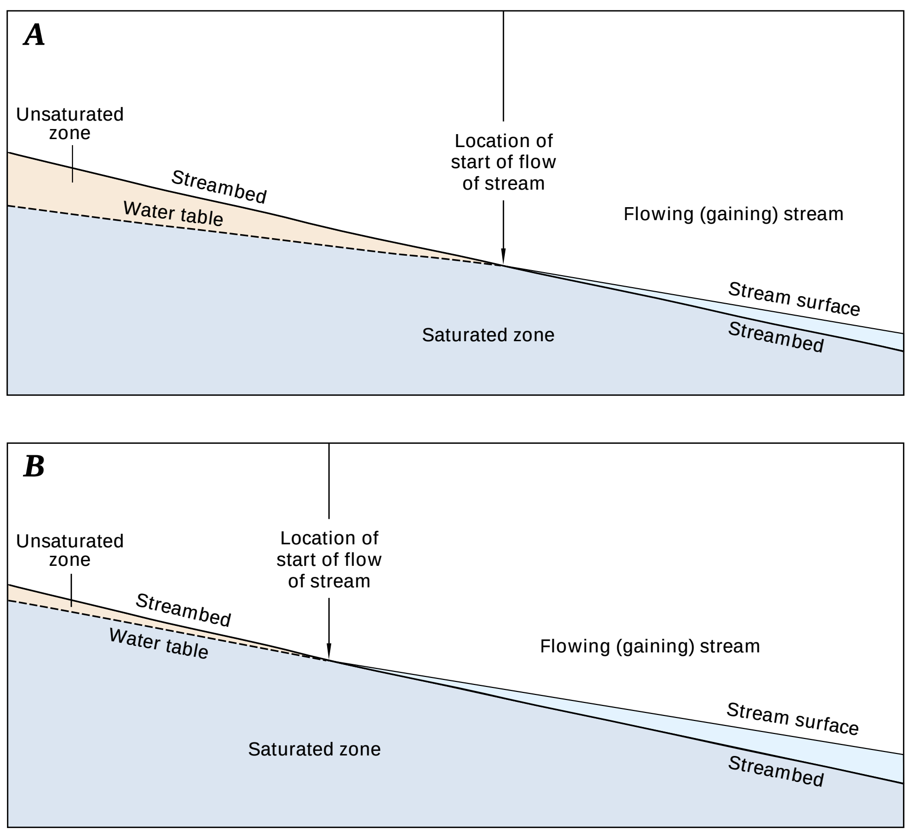


Figure ***13.*** *The location where perennial streamflow begins in a channel can vary depending on the distribution of recharge in headwaters areas. Following dry periods (A), the start of streamflow will move up-channel during wet periods as the ground-water system becomes more saturated (B).*

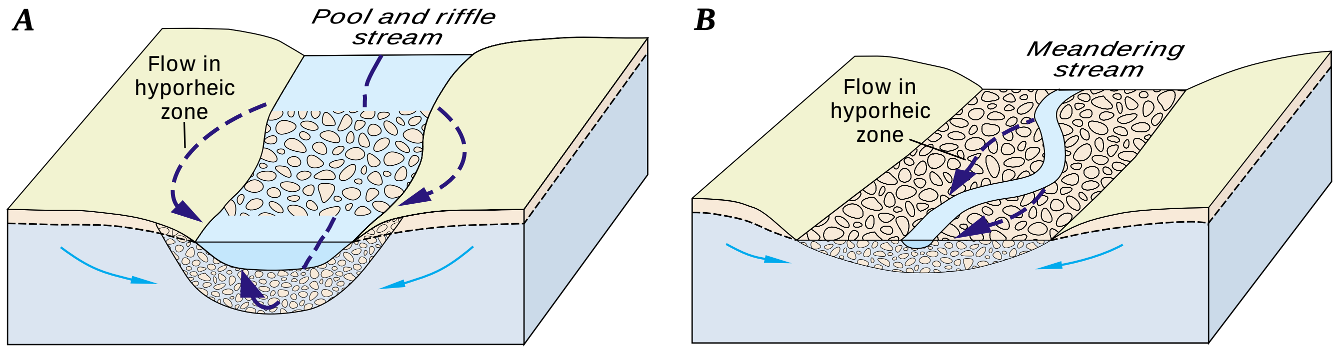


Figure 14. *Surface-water exchange with ground water in the hyporheic zone is associated with abrupt changes in streambed slope (A) and with stream meanders (B).*

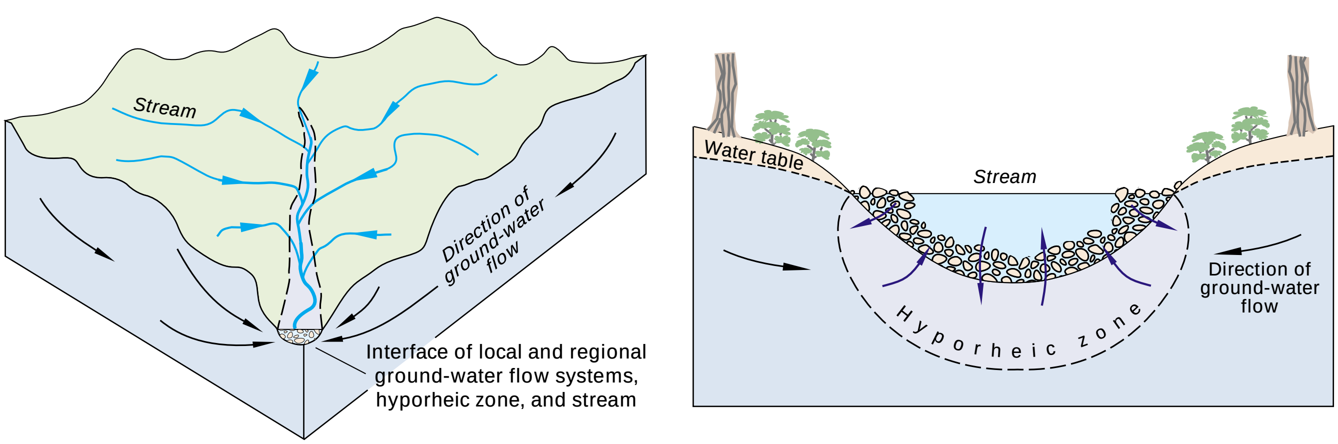


Figure 15. *Streambeds and banks are unique environments because they are where ground water that drains much of the subsurface of landscapes interacts with surface water that drains much of the surface of landscapes.*

INTERACTION OF GROUND WATER AND LAKES

Lakes interact with ground water in three basic ways: some receive ground-water inflow throughout their entire bed; some have seepage loss to ground water throughout their entire bed; but perhaps most lakes receive ground-water inflow through part of their bed and have seepage loss to ground water through other parts (Figure 16). Although these basic interactions are the same for lakes as they are for streams, the interactions differ in several ways.

The water level of natural lakes, that is, those not controlled by dams, generally does not change as rapidly as the water level of streams; therefore, bank storage is of lesser importance in lakes than it is in streams. Evaporation generally has a greater effect on lake levels than on stream levels because the surface area of lakes is generally larger and less shaded than many reaches of streams, and because lake water is not replenished as readily as a reach of a stream. Lakes can be present in many different parts of the landscape and can have complex ground-water flow systems associated with them. This is especially true for lakes in glacial and dune terrain, as is discussed in a later section of this Circular. Furthermore, lake sediments commonly have greater volumes of organic deposits than streams. These poorly permeable organic deposits can affect the distribution of seepage and biogeochemical exchanges of water and solutes more in lakes than in streams.

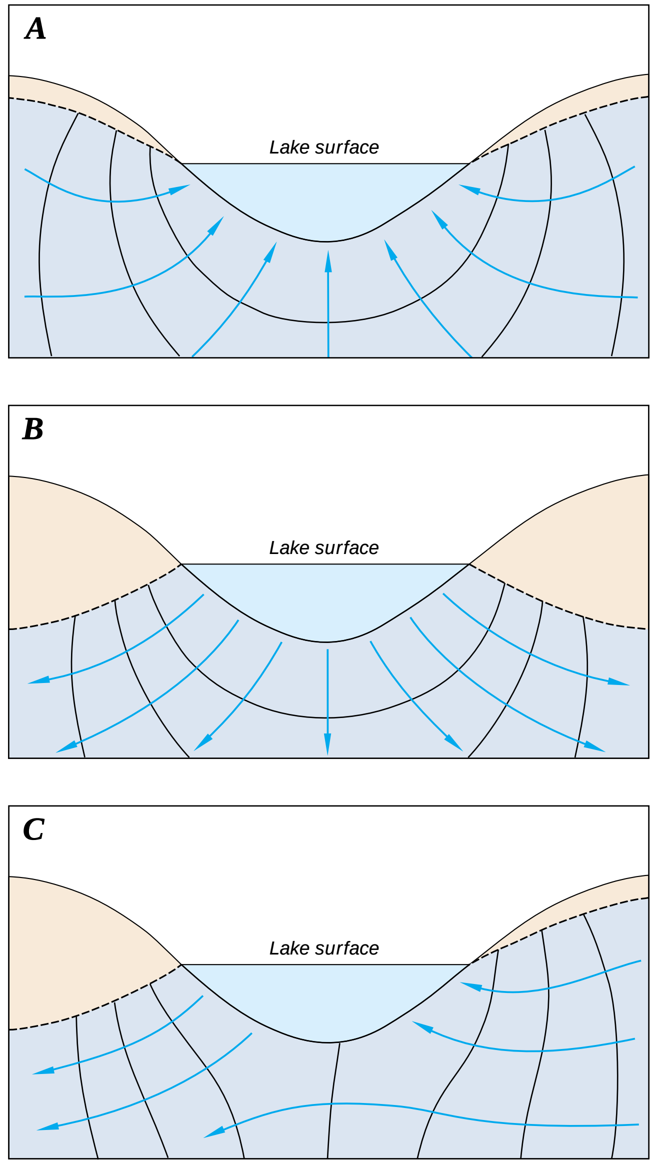


Figure 16. Lakes can receive ground-water inflow (A), lose water as seepage to ground water (B), or both

Reservoirs are human-made lakes that are designed primarily to control the flow and distribution of surface water. Most reservoirs are constructed in stream valleys; therefore, they have some characteristics both of streams and lakes. Like streams, reservoirs can have widely fluctuating levels, bank storage can be significant, and they commonly have a continuous flushing of water through them. Like lakes, reservoirs can have significant loss of water by evaporation, significant cycling of chemical and biological materials within their waters, and extensive biogeochemical exchanges of solutes with organic sediments.

"Lakes and wetlands can receive ground-water inflow throughout their entire bed, have outflow throughout their entire bed, or have both inflow and outflow at different localities"

INTERACTION OF GROUND WATER AND WETLANDS

Wetlands are present in climates and landscapes that cause ground water to discharge to land surface or that prevent rapid drainage of water from the land surface. Similar to streams and lakes, wetlands can receive ground-water inflow, recharge ground water, or do both. Those wetlands that occupy depressions in the land surface have interactions with ground water similar to lakes and streams. Unlike streams and lakes, however, wetlands do not always occupy low points and depressions in the landscape (Figure 17*A*); they also can be present on slopes (such as fens) or even on drainage divides (such as some types of bogs). Fens are wetlands that commonly receive ground-water discharge (Figure 17*B*); therefore, they receive a continuous supply of chemical constituents dissolved in the ground water. Bogs are wetlands that occupy uplands (Figure 17*D*) or extensive flat areas, and they receive much of their water and chemical constituents from precipitation. The distribution of major wetland areas in the United States is shown in Figure 18.

In areas of steep land slopes, the water table sometimes intersects the land surface, resulting in ground-water discharge directly to the land surface. The constant source of water at these seepage faces (Figure 17*B*) permits the growth of wetland plants. A constant source of ground water to wetland plants is also provided to parts of the landscape that are downgradient from breaks in slope of the water table (Figure 17*B*), and where subsurface discontinuities in geologic units cause upward movement of ground water (Figure 17*A*). Many wetlands are present along streams, especially slow-moving streams. Although these riverine wetlands (Figure 17*C*) commonly receive ground-water discharge, they are dependent primarily on the stream for their water supply.

Wetlands in riverine and coastal areas have especially complex hydrological interactions because they are subject to periodic water-level changes. Some wetlands in coastal areas are affected by very predictable tidal cycles. Other coastal wetlands and riverine wetlands are more affected by seasonal water-level changes and by flooding. The combined effects of precipitation, evapotranspiration, and interaction with surface water and ground water result in a pattern of water depths in wetlands that is distinctive.

Hydroperiod is a term commonly used in wetland science that refers to the amplitude and frequency of water-level fluctuations. Hydroperiod affects all wetland characteristics, including the type of vegetation, nutrient cycling, and the types of invertebrates, fish, and bird species present.

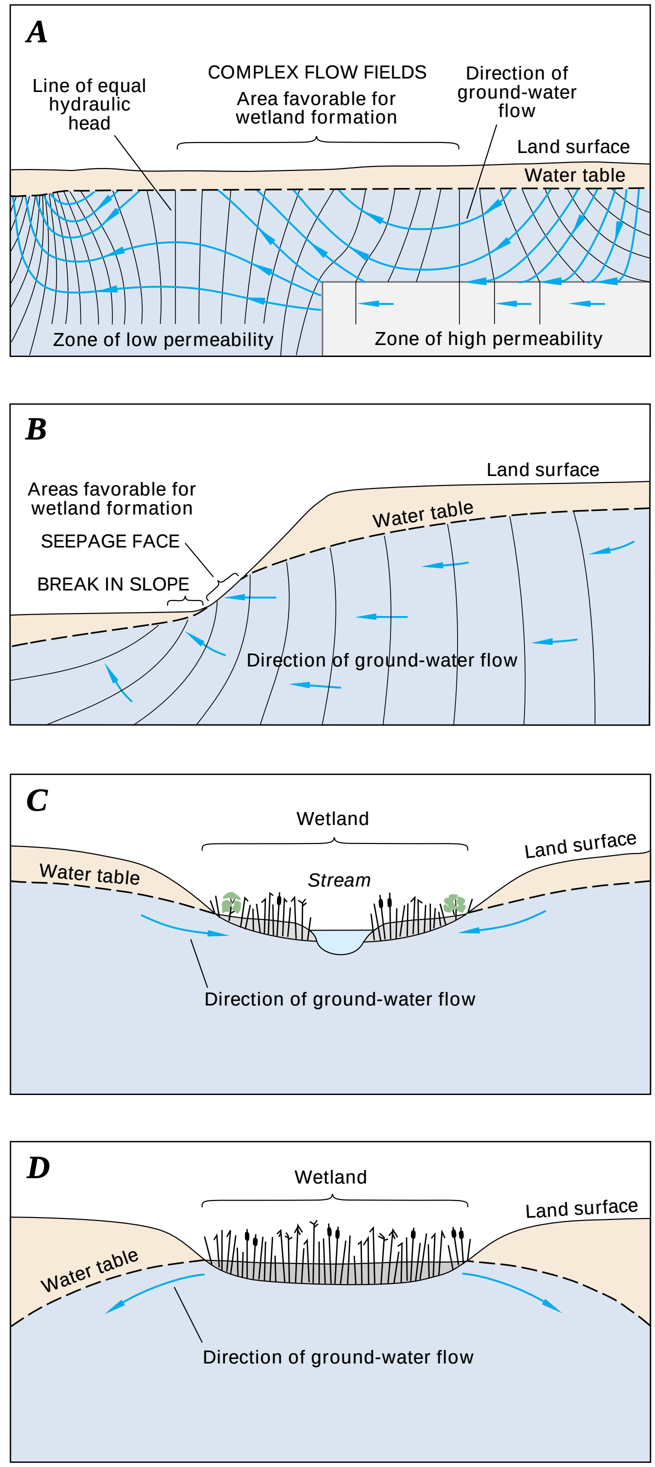


Figure 17. The source of water to wetlands can be from ground-water discharge where the land surface is underlain by complex ground-water flow fields (A), from ground-water discharge at seepage faces and at breaks in slope of the water table (B), from streams (C), and from precipitation in cases where wetlands have no stream inflow and ground-water gradients slope away from the wetland (D).

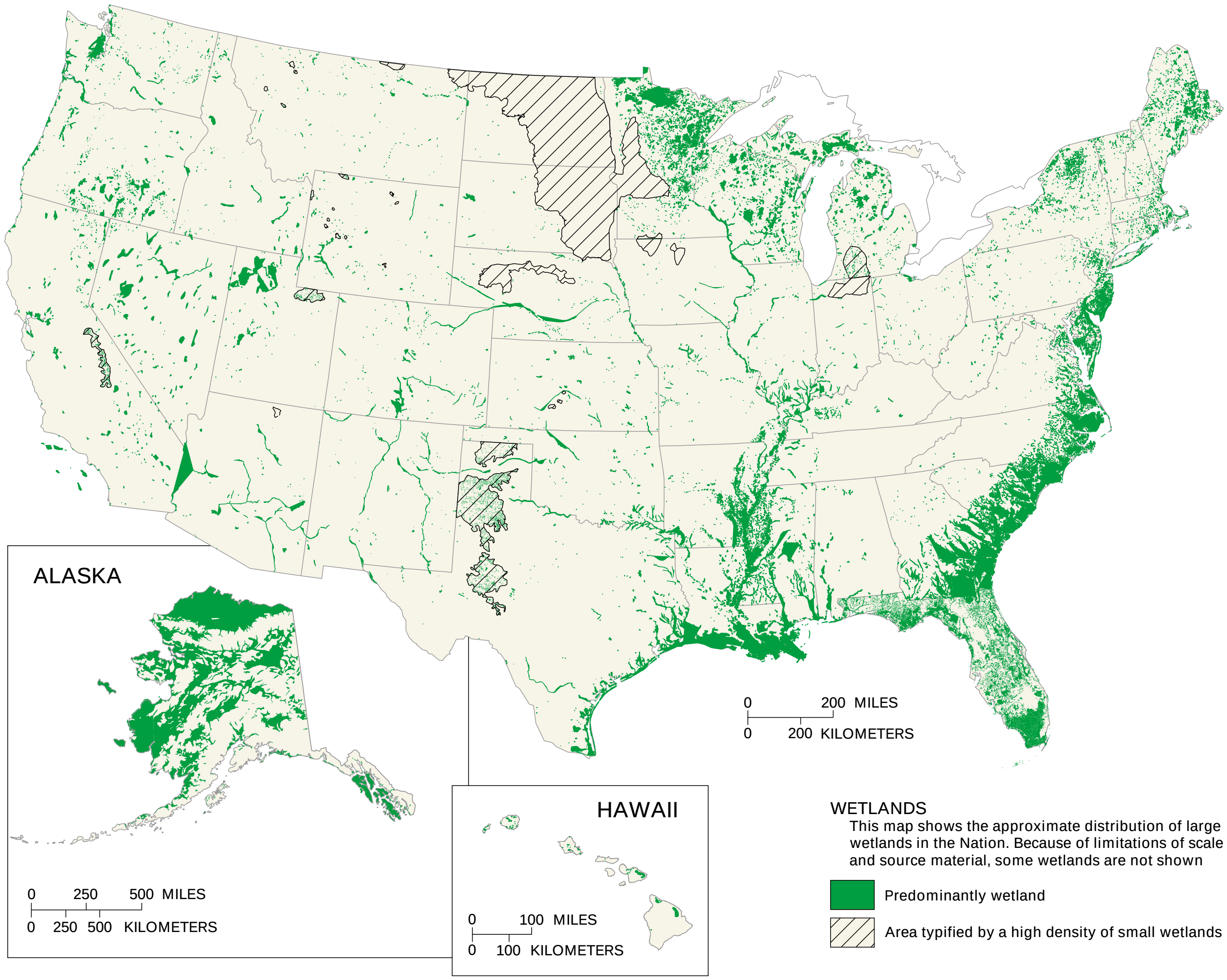


Figure ***18***. *Wetlands are present throughout the Nation, but they cover the largest areas in the glacial terrain of the north-central United States, coastal terrain along the Atlantic and gulf coasts, and riverine terrain in the lower Mississippi River Valley.*

A major difference between lakes and wetlands, with respect to their interaction with ground water, is the ease with which water moves through their beds. Lakes commonly are shallow around their perimeter where waves can remove fine-grained sediments, permitting the surface water and ground water to interact freely. In wetlands, on the other hand, if fine-grained and highly decomposed organic sediments are present near the wetland edge, the transfer of water and solutes between ground water and surface water is likely to be much slower.

Another difference in the interaction between ground water and surface water in wetlands compared to lakes is determined by rooted vegetation in wetlands. The fibrous root mat in wetland soils is highly conductive to water flow; therefore, water uptake by roots of emergent plants results in significant interchange between surface water and pore water of wetland sediments. The water exchanges in this upper soil zone even if exchange between surface water and ground water is restricted at the base of the wetland sediments.

Chemical Interactions of Ground Water and Surface Water

EVOLUTION OF WATER CHEMISTRY IN DRAINAGE BASINS

Two of the fundamental controls on water chemistry in drainage basins are the type of geologic materials that are present and the length of time that water is in contact with those materials. Chemical reactions that affect the biological and geochemical characteristics of a basin include (1) acid-base reactions, (2) precipitation and dissolution of minerals, (3) sorption and ion exchange, (4) oxidation-reduction reactions, (5) biodegradation, and (6) dissolution and exsolution of gases (see Box D). When water first infiltrates the land surface, microorganisms in the soil have a significant effect on the evolution of water chemistry. Organic matter in soils is degraded by microbes, producing high concentrations of dissolved carbon dioxide (CO_2). This process lowers the pH by increasing the carbonic acid (H_2CO_3) concentration in the soil water. The production of carbonic acid starts a number of mineral-weathering reactions, which result in bicarbonate (HCO_3^-) commonly being the most abundant anion in the water. Where contact times between water and minerals in shallow ground-water flow paths are short, the dissolved-solids concentration in the water generally is low. In such settings, limited chemical changes take place before ground water is discharged to surface water.

"Two of the fundamental controls on water chemistry in drainage basins are the type of geologic materials that are present and the length of time that water is in contact with those materials"

In deeper ground-water flow systems, the contact time between water and minerals is much longer than it is in shallow flow systems. As a result, the initial importance of reactions relating to microbes in the soil zone may be superseded over time by chemical reactions between minerals and water (geochemical weathering). As weathering progresses, the concentration of dissolved solids increases. Depending on the chemical composition of the minerals that are weathered, the relative abundance of the major inorganic chemicals dissolved in the water changes (see Box E).

Surface water in streams, lakes, and wetlands can repeatedly interchange with nearby ground water. Thus, the length of time water is in contact with mineral surfaces in its drainage basin can continue after the water first enters a stream, lake, or wetland. An important consequence of these continued interchanges between surface water and ground water is their potential to further increase the contact time between water and chemically reactive geologic materials.

CHEMICAL INTERACTIONS OF GROUND WATER AND SURFACE WATER IN STREAMS, LAKES, AND WETLANDS

Ground-water chemistry and surface-water chemistry cannot be dealt with separately where surface and subsurface flow systems interact. The movement of water between ground water and surface water provides a major pathway for chemical transfer between terrestrial and aquatic systems (see Box F). This transfer of chemicals affects the supply of carbon, oxygen, nutrients such as nitrogen and phosphorus, and other chemical constituents that enhance biogeochemical processes on both sides of the interface. This transfer can ultimately affect the biological and chemical characteristics of aquatic systems downstream.

"The movement of water between ground water and surface water provides a major pathway for chemical transfer between terrestrial and aquatic systems"

D

Some Common Types of Biogeochemical Reactions Affecting Transport of Chemicals in Ground Water and Surface Water

ACID-BASE REACTIONS

Acid-base reactions involve the transfer of hydrogen ions (H^+) among solutes dissolved in water, and they affect the effective concentrations of dissolved chemicals through changes in the H^+ concentration in water. A brief notation for H^+ concentration (activity) is pH, which represents a negative logarithmic scale of the H^+ concentration. Smaller values of pH represent larger concentrations of H^+, and larger values of pH represent smaller concentrations of H^+. Many metals stay dissolved when pH values are small; increased pH causes these metals to precipitate from solution.

PRECIPITATION AND DISSOLUTION OF MINERALS

Precipitation reactions result in minerals being formed (precipitated) from ions that are dissolved in water. An example of this type of reaction is the precipitation of iron, which is common in areas of ground-water seeps and springs. At these locations, the solid material iron hydroxide is formed when iron dissolved in ground water comes in contact with oxygen dissolved in surface water. The reverse, or dissolution reactions, result in ions being released into water by dissolving minerals. An example is the release of calcium ions (Ca^{++}) and bicarbonate ions (HCO_3^-) when calcite ($CaCO_3$) in limestone is dissolved.

SORPTION AND ION EXCHANGE

Sorption is a process in which ions or molecules dissolved in water (solutes) become attached to the surfaces (or near-surface parts) of solid materials, either temporarily or permanently. Thus, solutes in ground water and surface water can be sorbed either to the solid materials that comprise an aquifer or streambed or to particles suspended in ground water or surface water. The attachments of positively charged ions to clays and of pesticides to solid surfaces are examples of sorption. Release of sorbed chemicals to water is termed desorption.

When ions attached to the surface of a solid are replaced by ions that were in water, the process is known as ion exchange. Ion exchange is the process that takes place in water softeners; ions that contribute to water hardness—calcium and magnesium—are exchanged for sodium on the surface of the solid. The result of this process is that the amount of calcium and magnesium in the water declines and the amount of sodium increases. The opposite takes place when saltwater enters an aquifer; some of the sodium in the saltwater is exchanged for calcium sorbed to the solid material of the aquifer.

OXIDATION-REDUCTION REACTIONS

Oxidation-reduction (redox) reactions take place when electrons are exchanged among solutes. In these reactions, oxidation (loss of electrons) of certain elements is accompanied by the reduction (gain of electrons) of other elements.

For example, when iron dissolved in water that does not contain dissolved oxygen mixes with water that does contain dissolved oxygen, the iron and oxygen interact by oxidation and reduction reactions. The result of the reactions is that the dissolved iron loses electrons (the iron is oxidized) and oxygen gains electrons (the oxygen is reduced). In this case, the iron is an electron donor and the oxygen is an electron acceptor. Bacteria can use energy gained from oxidation-reduction reactions as they decompose organic material. To accomplish this, bacterially mediated oxidation-reduction reactions use a sequence of electron acceptors, including oxygen, nitrate, iron, sulfate, and carbon dioxide. The presence of the products of these reactions in ground water and surface water can be used to identify the dominant oxidation-reduction reactions that have taken place in those waters. For example, the bacterial reduction of sulfate (SO_4^{2-}) to sulfide (HS^-) can result when organic matter is oxidized to CO_2.

BIODEGRADATION

Biodegradation is the decomposition of organic chemicals by living organisms using enzymes. Enzymes are specialized organic compounds made by living organisms that speed up reactions with other organic compounds. Microorganisms degrade (transform) organic chemicals as a source of energy and carbon for growth. Microbial processes are important in the fate and transport of many organic compounds. Some compounds, such as petroleum hydrocarbons, can be used directly by microorganisms as food sources and are rapidly degraded in many situations. Other compounds, such as chlorinated solvents, are not as easily assimilated. The rate of biodegradation of an organic chemical is dependent on its chemical structure, the environmental conditions, and the types of microorganisms that are present. Although biodegradation commonly can result in complete degradation of organic chemicals to carbon dioxide, water, and other simple products, it also can lead to intermediate products that are of environmental concern. For example, deethylatrazine, an intermediate degradation product of the pesticide atrazine (see Box P), commonly is detected in water throughout the corn-growing areas of the United States.

DISSOLUTION AND EXSOLUTION OF GASES

Gases are directly involved in many geochemical reactions. One of the more common gases is carbon dioxide (CO_2). For example, stalactites can form in caves when dissolved CO_2 exsolves (degasses) from dripping ground water, causing pH to rise and calcium carbonate to precipitate. In soils, the microbial production of CO_2 increases the concentration of carbonic acid (H_2CO_3), which has a major control on the solubility of aquifer materials. Other gases commonly involved in chemical reactions are oxygen, nitrogen, hydrogen sulfide (H_2S), and methane (CH_4). Gases such as chlorofluorocarbons (CFCs) and radon are useful as tracers to determine the sources and rates of ground-water movement (see Box G).

E

Evolution of Ground-Water Chemistry from Recharge to Discharge Areas in the Atlantic Coastal Plain

Changes in the chemical composition of ground water in sediments of the Atlantic Coastal Plain (Figure E–1) provide an example of the chemical evolution of ground water in a regional flow system. In the shallow regime, infiltrating water comes in contact with gases in the unsaturated zone and shallow ground water. As a result of this contact, localized, short-term, fast reactions take place that dissolve minerals and degrade organic material. In the deep regime, long-term, slower chemical reactions, such as precipitation and dissolution of minerals and ion-exchange, add or remove solutes. These natural processes and reactions commonly produce a predictable sequence of hydrochemical facies. In the Atlantic Coastal Plain, ground water evolves from water containing abundant bicarbonate ions and small concentrations of dissolved solids near the point of recharge to water containing abundant chloride ions and large concentrations of dissolved solids where it discharges into streams, estuaries, and the Atlantic Ocean.

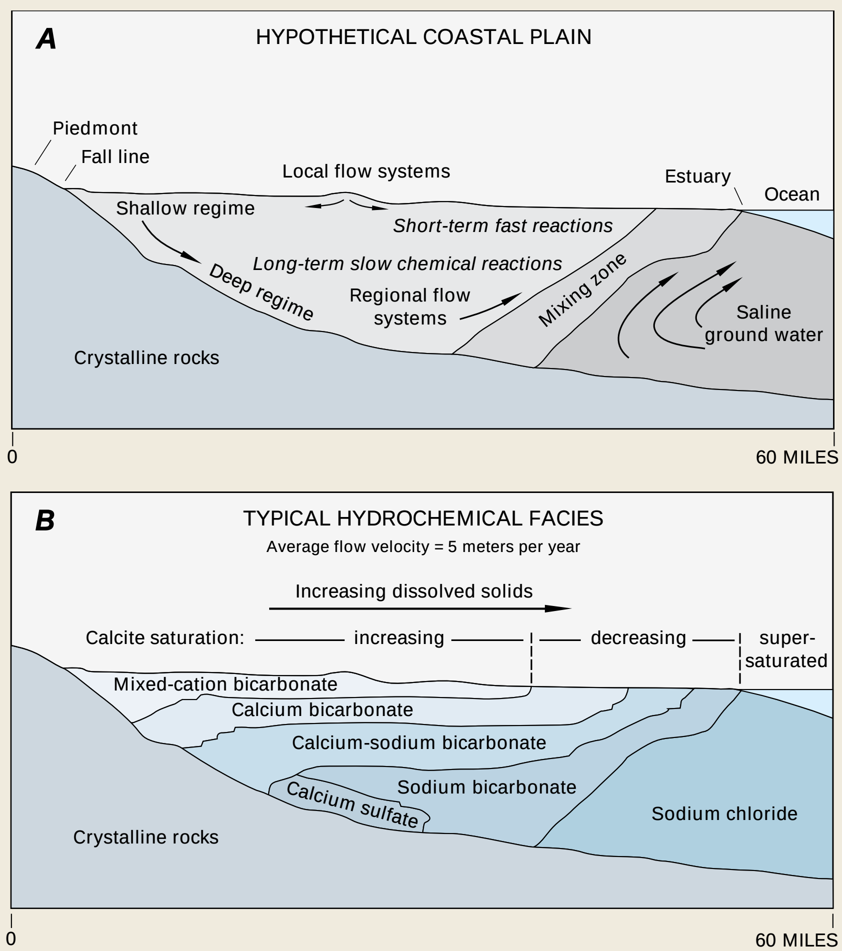


Figure E–1. In a coastal plain, such as along the Atlantic Coast of the United States, the interrelations of different rock types, shallow and deep ground-water flow systems (regimes), and mixing with saline water (A) results in the evolution of a number of different ground-water chemical types (B). (Modified from Back, William, Baedecker, M.J., and Wood, W.W., 1993, Scales in chemical hydrogeology—A historical perspective, in Alley, W.M., ed., Regional Ground-Water Quality: New York, van Nostrand Reinhold, p. 111–129.) (Reprinted by permission of John Wiley & Sons, Inc.)

Many streams are contaminated. Therefore, the need to determine the extent of the chemical reactions that take place in the hyporheic zone is widespread because of the concern that the contaminated stream water will contaminate shallow ground water (see Box G). Streams offer good examples of how interconnections between ground water and surface water affect chemical processes. Rough channel bottoms cause stream water to enter the streambed and to mix with ground water in the hyporheic zone. This mixing establishes sharp changes in chemical concentrations in the hyporheic zone.

A zone of enhanced biogeochemical activity usually develops in shallow ground water as a result of the flow of oxygen-rich surface water into the subsurface environment, where bacteria and geochemically active sediment coatings are abundant (Figure 19). This input of oxygen to the streambed stimulates a high level of activity by aerobic (oxygen-using) microorganisms if dissolved oxygen is readily available. It is not uncommon for dissolved oxygen to be completely used up in hyporheic flow paths at some distance into the streambed, where anaerobic microorganisms dominate microbial activity. Anaerobic bacteria can use nitrate, sulfate, or other solutes in place of oxygen for metabolism. The result of these processes is that many solutes are highly reactive in shallow ground water in the vicinity of streambeds.

The movement of nutrients and other chemical constituents, including contaminants, between ground water and surface water is affected by biogeochemical processes in the hyporheic zone. For example, the rate at which organic contaminants biodegrade in the hyporheic zone can exceed rates in stream water or in ground water away from the stream. Another example is the removal of dissolved metals in the hyporheic zone. As water passes through the hyporheic zone, dissolved metals are removed by precipitation of metal oxide coatings on the sediments.

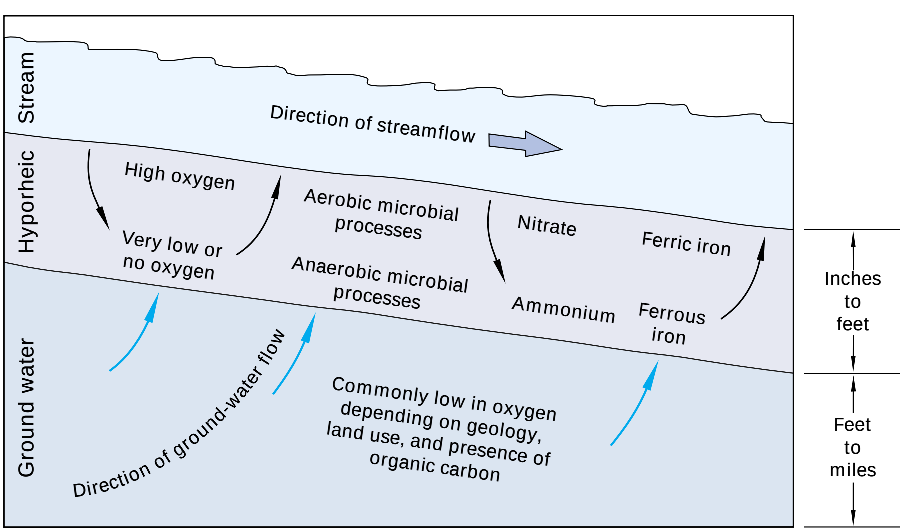


Figure *19*. *Microbial activity and chemical transformations commonly are enhanced in the hyporheic zone compared to those that take place in ground water and surface water. This diagram illustrates some of the processes and chemical transformations that may take place in the hyporheic zone. Actual chemical interactions depend on numerous factors including aquifer mineralogy, shape of the aquifer, types of organic matter in surface water and ground water, and nearby land use.*

F

The Interface Between Ground Water and Surface Water as an Environmental Entity

In the bed and banks of streams, water and solutes can exchange in both directions across the streambed. This process, termed hyporheic exchange, creates subsurface environments that have variable proportions of water from ground water and surface water. Depending on the type of sediment in the streambed and banks, the variability in slope of the streambed, and the hydraulic gradients in the adjacent ground-water system, the hyporheic zone can be as much as several feet in depth and hundreds of feet in width. The dimensions of the hyporheic zone generally increase with increasing width of the stream and permeability of streambed sediments.

The importance of the hyporheic zone was first recognized when higher than expected abundances of aquatic insects were found in sediments where concentrations of oxygen were high. Caused by stream-water input, the high oxygen concentrations in the hyporheic zone make it possible for organisms to live in the pore spaces in the sediments, thereby providing a refuge for those organisms. Also, spawning success of salmon is greater where flow from the stream brings oxygen into contact with eggs that were deposited within the coarse sediment.

The hyporheic zone also can be a source of nutrients and algal cells to streams that foster the recovery of streams following catastrophic storms. For example, in a study of the ecology of Sycamore Creek in Arizona, it was found that the algae that grew in the top few inches of streambed sediment were quickest to recover following storms in areas where water in the sediments moved upward (Figure F–1). These algae recovered rapidly following storms because concentrations of dissolved nitrogen were higher in areas of the streambed where water moved upward than in areas where water moved downward. Areas of streambed where water moved upward are, therefore, likely to be the first areas to return to more normal ecological conditions following flash floods in desert streams.

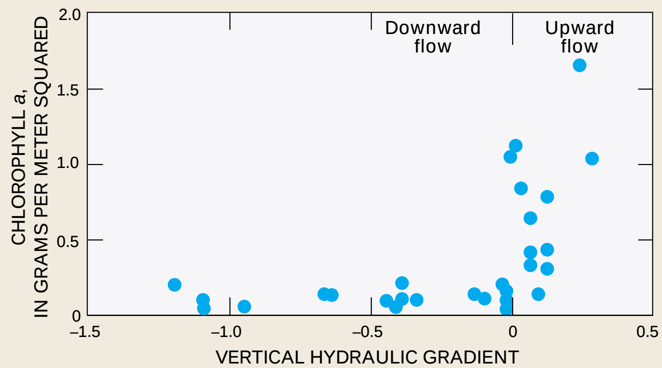


Figure F–1. Abundance of algae in streambed sediments, as indicated by concentration of chlorophyll a, *was markedly greater in areas where water moved upward through the sediments than in areas where water moved downward through the sediments in Sycamore Creek in Arizona. (Modified from Valett, H.M., Fisher, S.G., Grimm, N.B., and Camill, P., 1994, Vertical hydrologic exchange and ecologic stability of a desert stream ecosystem: Ecology, v. 75, p. 548–560.) (Reprinted with permission.)*

Hyporheic zones also serve as sites for nutrient uptake. A study of a coastal mountain stream in northern California indicated that transport of dissolved oxygen, dissolved carbon, and dissolved nitrogen in stream water into the hyporheic zone stimulated uptake of nitrogen by microbes and algae attached to sediment. A model simulation of nitrogen uptake (Figure F–2) indicated that both the physical process of water exchange between the stream and the hyporheic zone and the biological uptake of nitrate in the hyporheic zone affected the concentration of dissolved nitrogen in the stream.

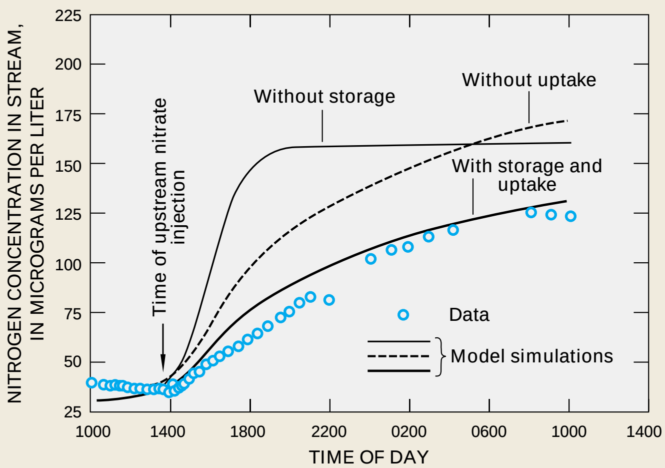


Figure F–2. Nitrate injected into Little Lost Man Creek in northern California was stored and taken up by algae and microbes in the hyporheic zone. (Modified from Kim, B.K.A., Jackman, A.P., and Triska, F.J., 1992, Modeling biotic uptake by periphyton and transient hyporheic storage of nitrate in a natural stream: Water Resources Research, v. 28, no.10, p. 2743–2752.)

The importance of biogeochemical processes that take place at the interface of ground water and surface water in improving water quality for human consumption is shown by the following example. Decreasing metal concentrations (Figure F–3) in drinking-water wells adjacent to the River Glatt in Switzerland was attributed to the interaction of the river with subsurface water. The improvement in ground-water quality started with improved sewage-treatment plants, which lowered phosphate in the river. Lower phosphate concentrations lowered the amount of algal production in the river, which decreased the amount of dissolved organic carbon flowing into the riverbanks. These factors led to a decrease in the bacteria-caused dissolution of manganese and cadmium that were present as coatings on sediment in the aquifer. The result was substantially lower dissolved metal concentrations in ground water adjacent to the river, which resulted in an unexpected improvement in the quality of drinking water.

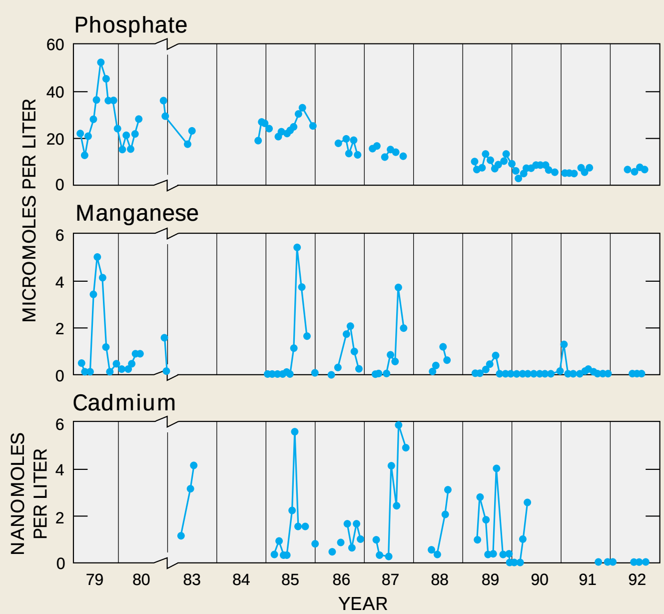
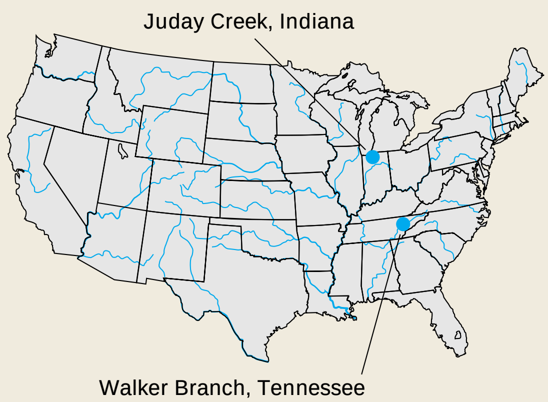


Figure F–3. A decline in manganese and cadmium concentrations after 1990 in drinking-water wells near the River Glatt in Switzerland was attributed to decreased phosphate in the river and hydrologic and biogeochemical interactions between river water and ground water. (Modified from von Gunten, H.R., and Lienert, Ch., 1993, Decreased metal concentrations in ground water caused by controls on phosphate emissions: Nature, v. 364, p. 220–222.) (Reprinted with permission from Nature, Macmillan Magazines Limited.)

G

Use of Environmental Tracers to Determine the Interaction of Ground Water and Surface Water

Environmental tracers are naturally occurring dissolved constituents, isotopes, or physical properties of water that are used to track the movement of water through watersheds. Useful environmental tracers include (1) common dissolved constituents, such as major cations and anions; (2) stable isotopes of oxygen (^{18}O) and hydrogen (^{2}H) in water molecules; (3) radioactive isotopes such as tritium (^{3}H) and radon (^{222}Rn); and (4) water temperature. When used in simple hydrologic transport calculations, environmental tracers can be used to (1) determine source areas of water and dissolved chemicals in drainage basins, (2) calculate hydrologic and chemical fluxes between ground water and surface water, (3) calculate water ages that indicate the length of time water and dissolved chemicals have been present in the drainage basin (residence times), and (4) determine average rates of chemical reactions that take place during transport. Some examples are described below.



Major cations and anions have been used as tracers in studies of the hydrology of small watersheds to determine the sources of water to streamflow during storms (see Figure G–1). In addition, stable isotopes of oxygen and hydrogen, which are part of water molecules, are useful for determining the mixing of waters from different source areas because of such factors as (1) differences in the isotopic composition of precipitation among recharge areas, (2) changes in the isotopic composition of shallow subsurface water caused by evaporation, and (3) temporal variability in the isotopic composition of precipitation relative to ground water.

Radioactive isotopes are useful indicators of the time that water has spent in the ground-water system. For example, tritium (^{3}H) is a well-known radioactive isotope of hydrogen that had peak concentrations in precipitation in the mid-1960s as a result of above-ground nuclear-bomb testing conducted at that time. Chlorofluorocarbons (CFCs), which are industrial chemicals that are present in ground water less than 50 years old, also can be used to calculate ground-water age in different parts of a drainage basin.

^{222}Radon is a chemically inert, radioactive gas that has a half-life of only 3.83 days. It is produced naturally in ground water as a product of the radioactive decay of ^{226}radium in uranium-bearing rocks and sediment. Several studies have documented that radon can be used to identify locations of

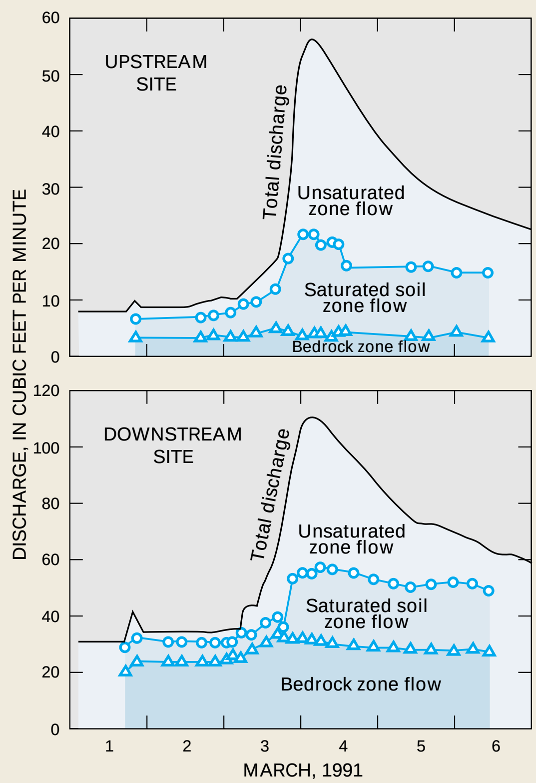


Figure G–1. The relative contributions of different subsurface water sources to streamflow in a stream in Tennessee were determined by analyzing the relative concentrations of calcium and sulfate. Note that increases in bedrock zone (ground water) flow appear to contribute more to the stormflow response at the downstream site than to the stormflow response at the upstream site in this small watershed. (Modified from Mulholland, P.J., 1993, Hydrometric and stream chemistry evidence of three storm flowpaths in Walker Branch Watershed: Journal of Hydrology, v. 151, p. 291–316.) (Reprinted with permission from Elsevier Science-NL, Amsterdam, The Netherlands.)

significant ground-water input to a stream, such as from springs. Radon also has been used to determine stream-water movement to ground water. For example, radon was used in a study in France to determine stream-water loss to ground water as a result of ground-water withdrawals. (See Figure G–2.)

An example of using stream-water temperature and sediment temperature for mapping gaining and losing reaches of a stream is shown in Figure G–3. In gaining reaches of the stream, sediment temperature and stream-water temperature are markedly different. In losing reaches of the stream, the diurnal fluctuations of temperature in the stream are reflected more strongly in the sediment temperature.

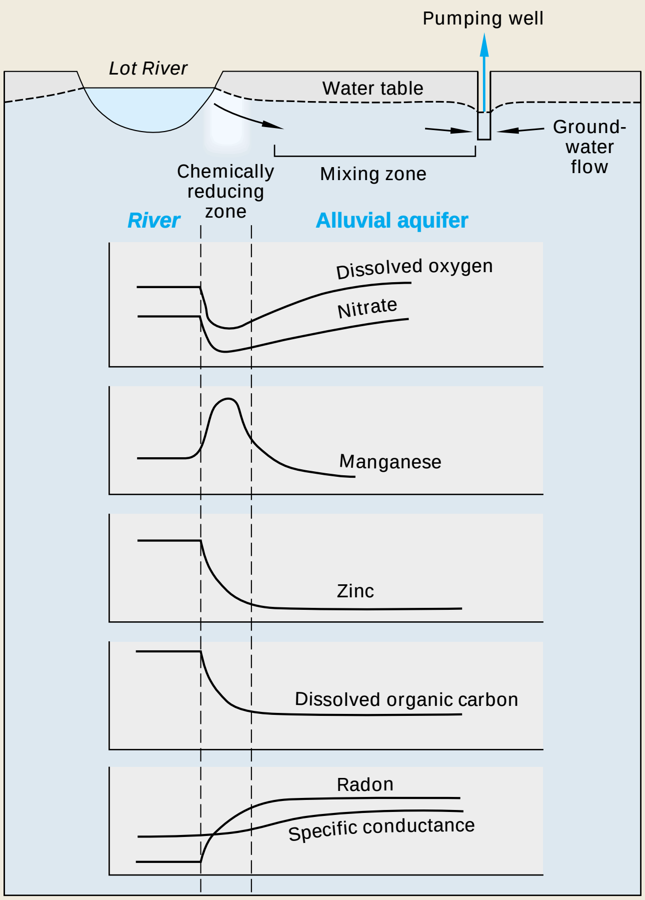


Figure G–2. Sharp changes in chemical concentrations were detected over short distances as water from the Lot River in France moved into its contiguous alluvial aquifer in response to pumping from a well. Specific conductance of water was used as an environmental tracer to determine the extent of mixing of surface water with ground water, and radon was used to determine the inflow rate of stream water. Both pieces of information were then used to calculate the rate at which dissolved metals reacted to form solid phases during movement of stream water toward the pumping well. (Modified from Bourg, A.C.M., and Bertin, C., 1993, Biogeochemical processes during the infiltration of river water into an alluvial aquifer: Environmental Science and Technology, v. 27, p. 661–666.) (Reprinted with permission from the American Chemical Society.)

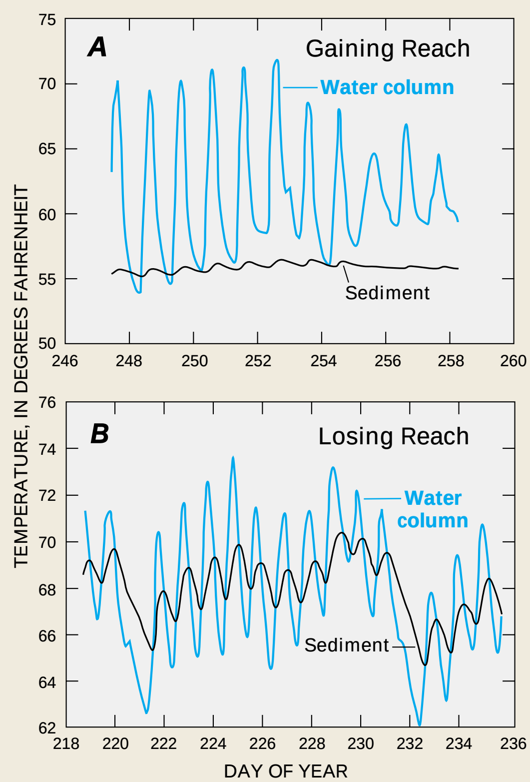


Figure G–3. Ground-water temperatures generally are more stable than surface-water temperatures. Therefore, gaining reaches of Juday Creek in Indiana are characterized by relatively stable sediment temperatures compared to stream-water temperatures (A). Conversely, losing reaches are characterized by more variable sediment temperatures caused by the temperature of the inflowing surface water (B). (Modified from Silliman, S.E., and Booth, D.F., 1993, Analysis of time series measurements of sediment temperature for identification of gaining versus losing portions of Juday Creek, Indiana: Journal of Hydrology, v. 146, p. 131–148.) (Reprinted with permission from Elsevier Science-NL, Amsterdam, The Netherlands.)

Lakes and wetlands also have distinctive biogeochemical characteristics with respect to their interaction with ground water. The chemistry of ground water and the direction and magnitude of exchange with surface water significantly affect the input of dissolved chemicals to lakes and wetlands. In general, if lakes and wetlands have little interaction with streams or with ground water, input of dissolved chemicals is mostly from precipitation; therefore, the input of chemicals is minimal. Lakes and wetlands that have a considerable amount of ground-water inflow generally have large inputs of dissolved chemicals. In cases where the input of dissolved nutrients such as phosphorus and nitrogen exceeds the output, primary production by algae and wetland plants is large. When this large amount of plant material dies, oxygen is used in the process of decomposition. In some cases the loss of oxygen from lake water can be large enough to kill fish and other aquatic organisms.

The magnitude of surface-water inflow and outflow also affects the retention of nutrients in wetlands. If lakes or wetlands have no stream outflow, retention of chemicals is high. The tendency to retain nutrients usually is less in wetlands that are flushed substantially by throughflow of surface water. In general, as surface-water inputs increase, wetlands vary from those that strongly retain nutrients to those that both import and export large amounts of nutrients. Furthermore, wetlands commonly have a significant role in altering the chemical form of dissolved constituents. For example, wetlands that have throughflow of surface water tend to retain the chemically oxidized forms and release the chemically reduced forms of metals and nutrients.

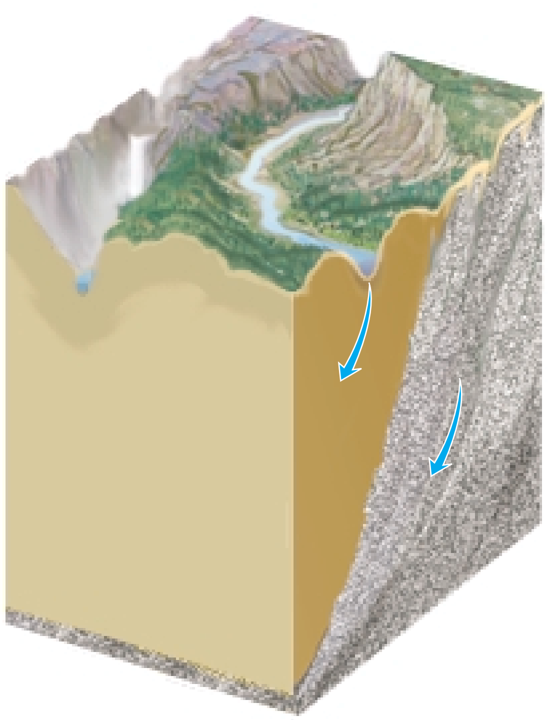
"The chemistry of ground water and the direction and magnitude of exchange with surface water significantly affect the input of dissolved chemicals to lakes and wetlands"

Interaction of Ground Water and Surface Water in Different Landscapes

Ground water is present in virtually all landscapes. The interaction of ground water with surface water depends on the physiographic and climatic setting of the landscape. For example, a stream in a wet climate might receive ground-water inflow, but a stream in an identical physiographic setting in an arid climate might lose water to ground water. To provide a broad and unified perspective of the interaction of ground water and surface water in different landscapes, a conceptual landscape (Figure 2) is used as a reference. Some common features of the interaction for various parts of the conceptual landscape are described below. The five general types of terrain discussed are mountainous, riverine, coastal, glacial and dune, and karst.

MOUNTAINOUS TERRAIN

The hydrology of mountainous terrain (area M of the conceptual landscape, Figure 2) is characterized by highly variable precipitation and water movement over and through steep land slopes. On mountain slopes, macropores created by burrowing organisms and by decay of plant roots have the capacity to transmit subsurface flow downslope quickly. In addition, some rock types underlying soils may be highly weathered or fractured and may transmit significant additional amounts of flow through the subsurface. In some settings this rapid flow of water results in hillside springs.



A general concept of water flow in mountainous terrain includes several pathways by which precipitation moves through the hillside to a stream (Figure 20). Between storm and snowmelt periods, streamflow is sustained by discharge from the ground-water system (Figure 20*A*). During intense storms, most water reaches streams very rapidly by partially saturating and flowing through the highly conductive soils. On the lower parts of hillslopes, the water table sometimes rises to the land surface during storms, resulting in overland flow (Figure 20*B*). When this occurs, precipitation on the saturated area adds to the quantity of overland flow. When storms or snowmelt persist in mountainous areas, near-stream saturated areas can expand outward from streams to include areas higher on the hillslope. In some settings, especially in arid regions, overland flow can be generated when the rate of rainfall exceeds the infiltration capacity of the soil (Figure 20*C*).

Near the base of some mountainsides, the water table intersects the steep valley wall some distance up from the base of the slope (Figure 21, left side of valley). This results in perennial

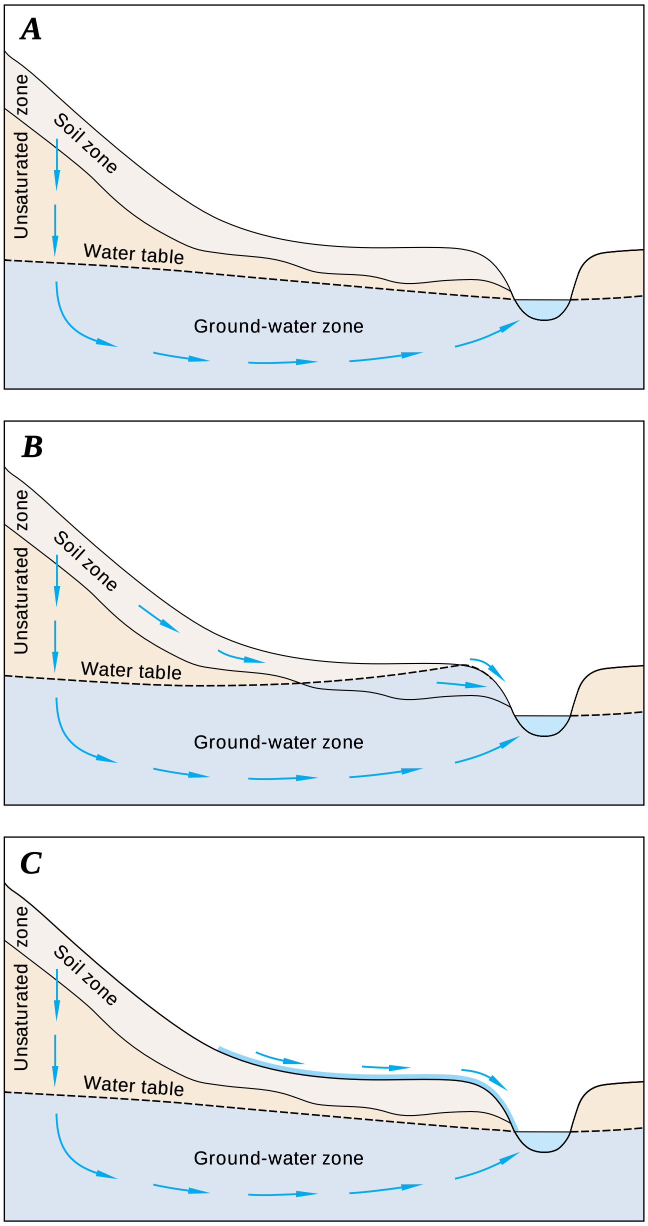


Figure 20. Water from precipitation moves to mountain streams along several pathways. Between storms and snowmelt periods, most inflow to streams commonly is from ground water (A). During storms and snowmelt periods, much of the water inflow to streams is from shallow flow in saturated macropores in the soil zone. If infiltration to the water table is large enough, the water table will rise to the land surface and flow to the stream is from ground water, soil water, and overland runoff (B). In arid areas where soils are very dry and plants are sparse, infiltration is impeded and runoff from precipitation can occur as overland flow (C). (Modified from Dunne, T., and Leopold, L.B., 1978, Water in environmental planning: San Francisco, W.H. Freeman.) (Used with permission.)

discharge of ground water and, in many cases, the presence of wetlands. A more common hydrologic process that results in the presence of wetlands in some mountain valleys is the upward discharge of ground water caused by the change in slope of the water table from being steep on the valley side to being relatively flat in the alluvial valley (Figure 21, right side of valley). Where both of these water-table conditions exist, wetlands fed by ground water, which commonly are referred to as fens, can be present.

Another dynamic aspect of the interaction of ground water and surface water in mountain settings is caused by the marked longitudinal component of flow in mountain valleys. The high gradient of mountain streams, coupled with the coarse texture of streambed sediments, results in a strong down-valley component of flow accompanied by frequent exchange of stream water with water in the hyporheic zone (Figure 14) (see Box H). The driving force for water exchange between a stream and its hyporheic zone is created by the surface water flowing over rough streambeds, through pools and riffles, over cascades, and around boulders and logs. Typically, the stream enters the hyporheic zone at the downstream end of pools and then flows beneath steep sections of the stream (called riffles), returning to the stream at the upstream end of the next pool (Figure 14*A*). Stream water also may enter the hyporheic zone upstream from channel meanders, causing stream water to flow through a gravel bar before reentering the channel downstream (Figure 14*B*).

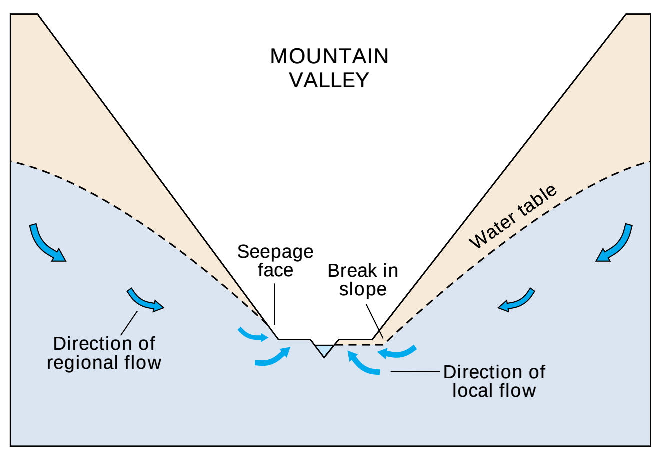


Figure 21. In mountainous terrain, ground water can discharge at the base of steep slopes (left side of valley), at the edges of flood plains (right side of valley), and to the stream.

Streams flowing from mountainous terrain commonly flow across alluvial fans at the edges of the valleys. Most streams in this type of setting lose water to ground water as they traverse the highly permeable alluvial fans. This process has long been recognized in arid western regions, but it also has been documented in humid regions, such as the Appalachian Mountains. In arid and semiarid regions, seepage of water from the stream can be the principal source of aquifer recharge. Despite its importance, ground-water recharge from losing streams remains a highly uncertain part of the water balance of aquifers in these regions. Promising new methods of estimating ground-water recharge, at least locally, along mountain fronts are being developed—these methods include use of environmental tracers, measuring vertical temperature profiles in streambeds, measuring hydraulic characteristics of streambeds, and measuring the difference in hydraulic head between the stream and the underlying aquifer.

The most common natural lakes in mountainous terrain are those that are dammed by rock sills or glacial deposits high in the mountains. Termed cirque lakes, they receive much of their water from snowmelt. However, they interact with ground water much like the processes shown in Figure 21, and they can be maintained by ground water throughout the snow-free season.

The geochemical environment of mountains is quite diverse because of the effects of highly variable climate and many different rock and soil types on the evolution of water chemistry. Geologic materials can include crystalline, volcanic, and sedimentary rocks and glacial deposits. Sediments can vary from those having well-developed soil horizons to stream alluvium that has no soil development. During heavy precipitation, much water flows through shallow flow paths, where it interacts with microbes and soil gases. In the deeper flow through fractured bedrock, longer term geochemical interactions of ground water with minerals determine the chemistry of water that eventually discharges to streams. Base flow of streams in mountainous terrain is derived by drainage from saturated alluvium in valley bottoms and from drainage of bedrock fractures. Mixing of these chemically different water types results in geochemical reactions that affect the chemistry of water in streams. During downstream transport in the channel, stream water mixes with ground water in the hyporheic zone. In some mountain streams, the volume of water in the hyporheic zone is considerably larger than that in the stream channel. Chemical reactions in hyporheic zones can, in some cases, substantially alter the water chemistry of streams (Figure 19).

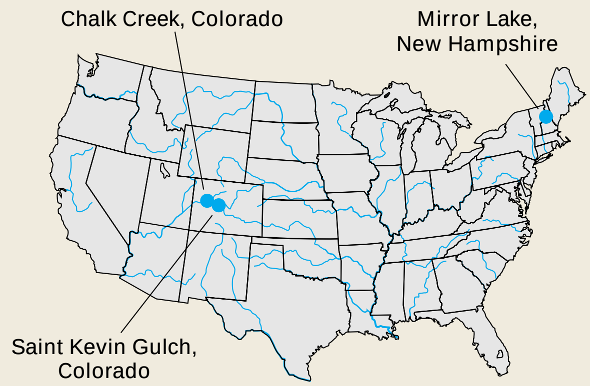
H

Field Studies of Mountainous Terrain

The steep slopes and rocky characteristics of mountainous terrain make it difficult to determine interactions of ground water and surface water. Consequently, few detailed hydrogeologic investigations of these interactions have been conducted in mountainous areas. Two examples are given below.

A field and modeling study of the Mirror Lake area in the White Mountains of New Hampshire indicated that the sizes of ground-water flow systems contributing to surface-water bodies were considerably larger than their topographically defined watersheds. For example, much of the ground water in the fractured bedrock that discharges to Mirror Lake passes beneath the local flow system associated with Norris Brook (Figure H–1). Furthermore, a more extensive deep ground-water flow system that discharges to the Pemigewasset River passes beneath flow systems associated with both Norris Brook and Mirror Lake.

Studies in mountainous terrain have used tracers to determine sources of ground water to streams (see Box G). In addition to revealing processes of water exchange between ground water and stream water, solute tracers have proven useful for defining the limits of the hyporheic zone surrounding mountain streams. For example, solute tracers such as chloride or bromide ions are injected into the stream to artificially raise concentrations above natural background concentrations. The locations and amounts of ground-water inflow are determined from a simple dilution model. The extent that tracers move into the hyporheic zone can be estimated by the models and commonly is verified by sampling wells placed in the study area.



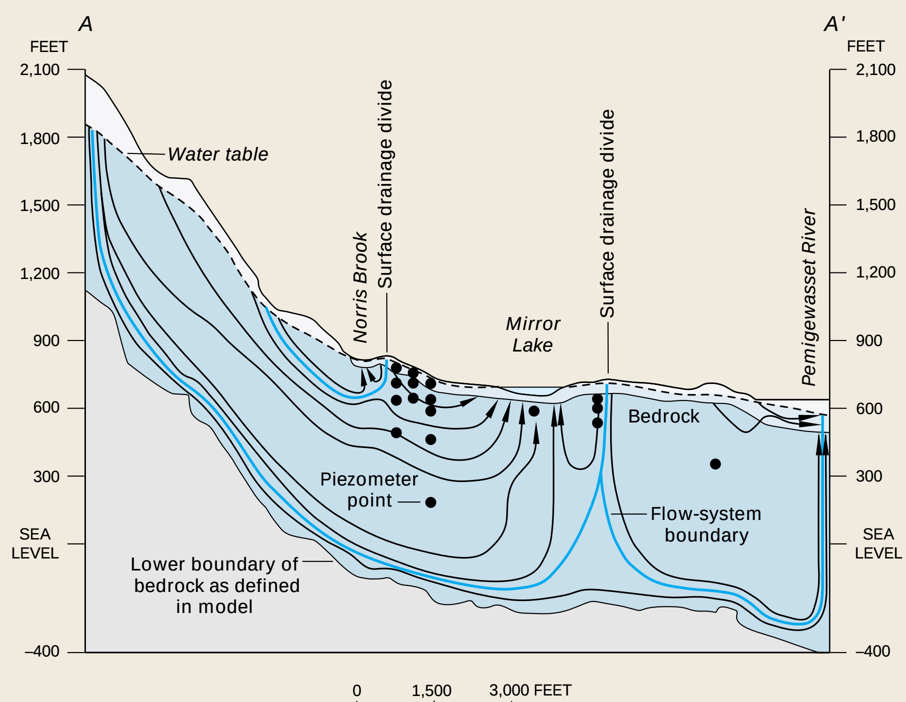


Figure H–1. Ground-water flow systems in the Mirror Lake area extend beyond the topographically defined surface-water watersheds. (Modified from Harte, P.T., and Winter, T.C., 1996, Factors affecting recharge to crystalline rock in the Mirror Lake area, Grafton County, New Hampshire: in Morganwalp, D.W., and Aronson, D.A., eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of Technical Meeting, Colorado Springs, Colorado, September 20–24, 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4014, p. 141–150.)

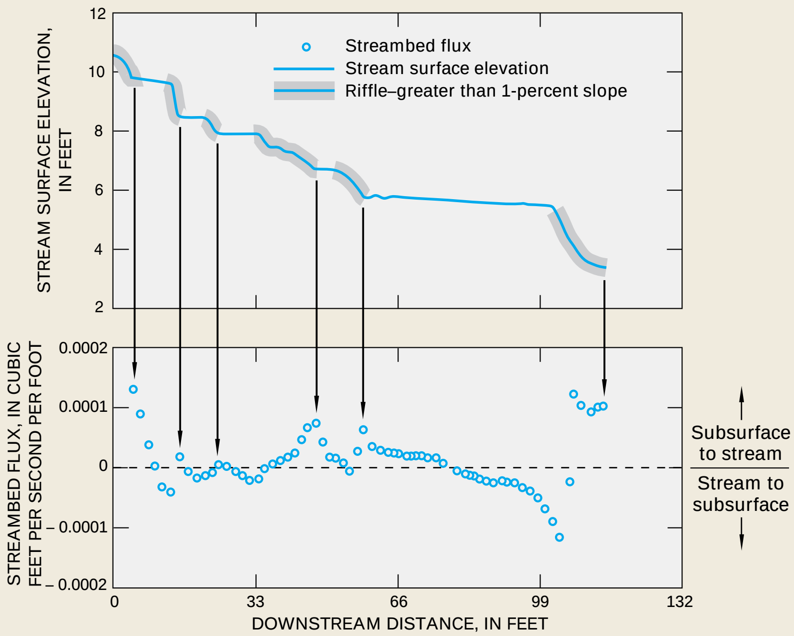


Figure H–2. In mountain streams characterized by pools and riffles, such as at Saint Kevin Gulch in Colorado, inflow of water from the hyporheic zone to the stream was greatest at the downstream end of riffles. (Modified from Harvey, J.W., and Bencala, K.E., 1993, The effect of streambed topography on surface-subsurface water exchange in mountain catchments: Water Resources Research, v. 29, p. 89–98.)

A study in Colorado indicated that hyporheic exchange in mountain streams is caused to a large extent by the irregular topography of the streambed, which creates pools and riffles characteristic of mountain streams. Ground water enters streams most readily at the upstream end of deep pools, and stream water flows into the subsurface beneath and to the side of steep sections of streams (riffles) (Figure H–2). Channel irregularity, therefore, is an important control on the location of ground-water inflow to streams and on the size of the hyporheic zone in mountain streams because changes in slope determine the length and depth of hyporheic flow paths.

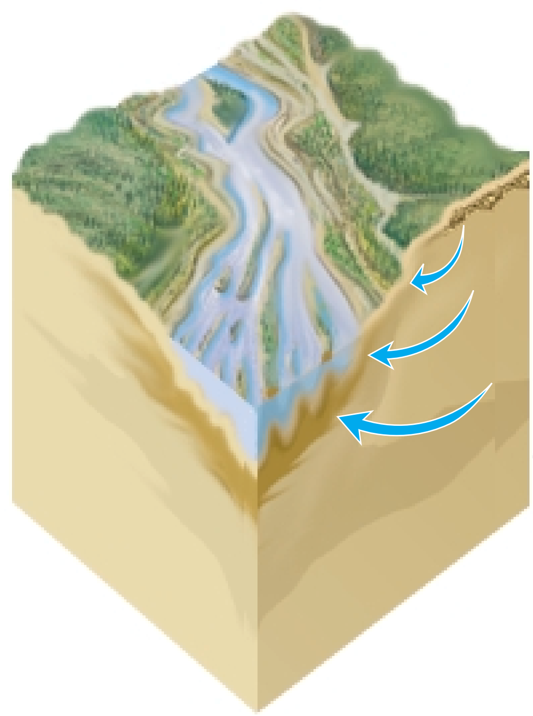
The source and fate of metal contaminants in streams receiving drainage from abandoned mines can be determined by using solute tracers. In addition to surface drainage from mines, a recent study of Chalk Creek in Colorado indicated that contaminants were being brought to the stream by ground-water inflow. The ground water had been contaminated from mining activities in the past and is now a new source of contamination to the stream. This nonpoint ground-water source of contamination will very likely be much more difficult to clean up than the point source of contamination from the mine tunnel.

RIVERINE TERRAIN

In some landscapes, stream valleys are small and they commonly do not have well-developed flood plains (area R of the conceptual landscape, Figure 2) (see Box I). However, major rivers (area V of the reference landscape, Figure 2) have valleys that usually become increasingly wider downstream. Terraces, natural levees, and abandoned river meanders are common landscape features in major river valleys, and wetlands and lakes commonly are associated with these features.

The interaction of ground water and surface water in river valleys is affected by the interchange of local and regional ground-water flow systems with the rivers and by flooding and evapotranspiration. Small streams receive ground-water inflow primarily from local flow systems, which usually have limited extent and are highly variable seasonally. Therefore, it is not unusual for small streams to have gaining or losing reaches that change seasonally.

For larger rivers that flow in alluvial valleys, the interaction of ground water and surface water usually is more spatially diverse than it is for smaller streams. Ground water from regional flow systems discharges to the river as well as at various places across the flood plain (Figure 22). If terraces are present in the alluvial valley, local ground-water flow systems may be associated with each terrace, and lakes and wetlands may be formed because of this source of ground water. At some locations, such as at the valley wall and at the river, local and regional ground-water flow systems may discharge in close proximity. Furthermore, in large alluvial valleys, significant down-valley components of flow in the streambed and in the shallow alluvium also may be present (see Box I).



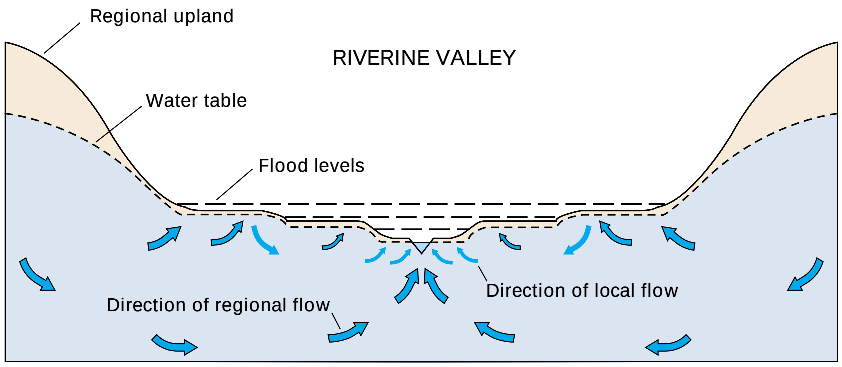


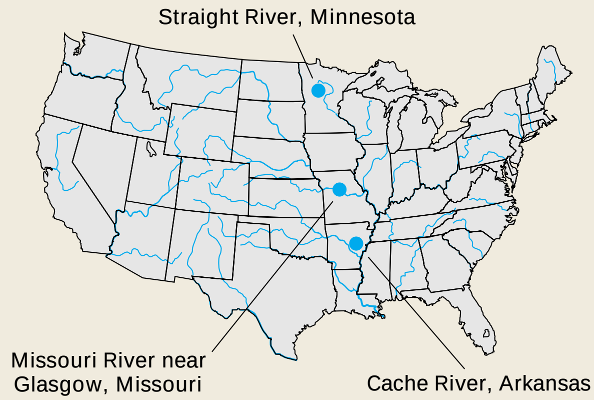
Figure 22. In broad river valleys, small local ground-water flow systems associated with terraces overlie more regional ground-water flow systems. Recharge from flood waters superimposed on these ground-water flow systems further complicates the hydrology of river

Added to this distribution of ground-water discharge from different flow systems to different parts of the valley is the effect of flooding. At times of high river flows, water moves into the ground-water system as bank storage (Figure 11). The flow paths can be as lateral flow through the river-bank (Figure 12*B*) or, during flooding, as vertical seepage over the flood plain (Figure 12*C*). As flood waters rise, they cause bank storage to move into higher and higher terraces.

The water table generally is not far below the land surface in alluvial valleys. Therefore, vegetation on flood plains, as well as at the base of some terraces, commonly has root systems deep enough so that the plants can transpire water directly from ground water. Because of the relatively stable source of ground water, particularly in areas of ground-water discharge, the vegetation can transpire water near the maximum potential transpiration rate, resulting in the same effect as if the water were being pumped by a well (see Figure 7). This large loss of water can result in drawdown of the water table such that the plants intercept some of the water that would otherwise flow to the river, wetland, or lake. Furthermore, in some settings it is not uncommon during the growing season for the pumping effect of transpiration to be significant enough that surface water moves into the subsurface to replenish the transpired ground water.

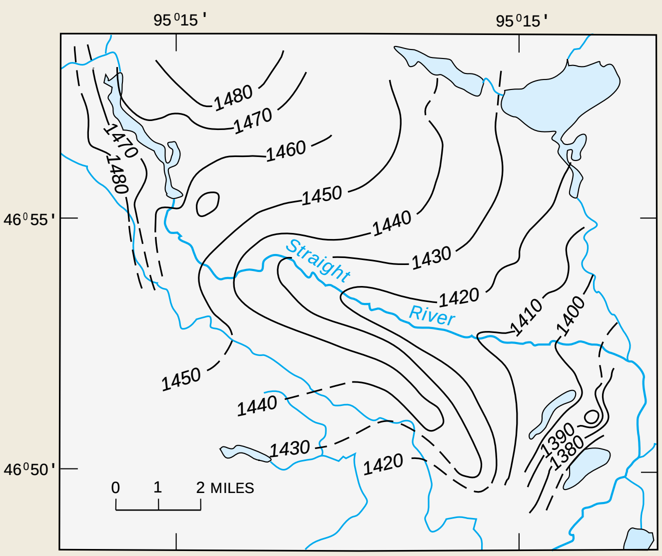
Riverine alluvial deposits range in size from clay to boulders, but in many alluvial valleys, sand and gravel are the predominant deposits. Chemical reactions involving dissolution or precipitation of minerals (see Box D) commonly do not have a significant effect on water chemistry in sand and gravel alluvial aquifers because the rate of water movement is relatively fast compared to weathering rates. Instead, sorption and desorption reactions and oxidation/reduction reactions related to the activity of microorganisms probably have a greater effect on water chemistry in these systems. As in small streams, biogeochemical processes in the hyporheic zone may have a significant effect on the chemistry of ground water and surface water in larger riverine systems. Movement of oxygen-rich surface water into the subsurface, where chemically reactive sediment coatings are abundant, causes increased chemical reactions related to activity of microorganisms. Sharp gradients in concentration of some chemical constituents in water, which delimit this zone of increased biogeochemical activity, are common near the boundary between ground water and surface water. In addition, chemical reactions in the hyporheic zone can cause precipitation of some reactive solutes and contaminants, thereby affecting water quality.

Field Studies of Riverine Terrain



Streams are present in virtually all landscapes, and in some landscapes, they are the principal surface-water features. The interaction of ground water with streams varies in complexity because they vary in size from small streams near headwaters areas to large rivers flowing in large alluvial valleys, and also because streams intersect ground-water flow systems of greatly different scales. Examples of the interaction of ground water and surface water for small and large riverine systems are presented below.

The Straight River, which runs through a sand plain in central Minnesota, is typical of a small stream that does not have a flood plain and that derives most of its water from ground-water inflow. The water-table contours near the river bend sharply upstream (Figure I–1), indicating that ground water moves directly into the river. It is estimated from base-flow studies (see Box B) that, on an annual basis, ground water accounts for more than 90 percent of the water in the river.



EXPLANATION

—1420— WATER-TABLE CONTOUR—Shows altitude of the water table in feet above sea level. Dashed where approximately located. Contour interval 10 feet

Figure I–1. Small streams, such as the Straight River in Minnesota, commonly do not have flood plains. The flow of ground water directly into the river is indicated by the water-table contours that bend sharply upstream. (Modified from Stark, J.R., Armstrong, D.S., and Zwilling, D.R., 1994, Stream-aquifer interactions in the Straight River area, Becker and Hubbard Counties, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 94–4009, 83 p.)

In contrast, the results of a study of the lower Missouri River Valley indicate the complexity of ground-water flow and its interaction with streams in large alluvial valleys. Configuration of the water table in this area indicates that ground water flows into the river at right angles in some reaches, and it flows parallel to the river in others (Figure I–2*A*). This study also resulted in a map that showed patterns of water-table fluctuations with respect to proximity to the river (Figure I–2*B*). This example shows the wide variety of ground-water flow conditions that can be present in large alluvial valleys.

Another study of part of a large alluvial valley provides an example of the presence of smaller scale flow conditions. The Cache River is a stream within the alluvial valley of the Mississippi River Delta system in eastern Arkansas. In a study of the Black Swamp, which lies along a reach of the river, a number of wells and piezometers were installed to determine the interaction of ground water with the swamp and the river. By measuring hydraulic head at different depths in the

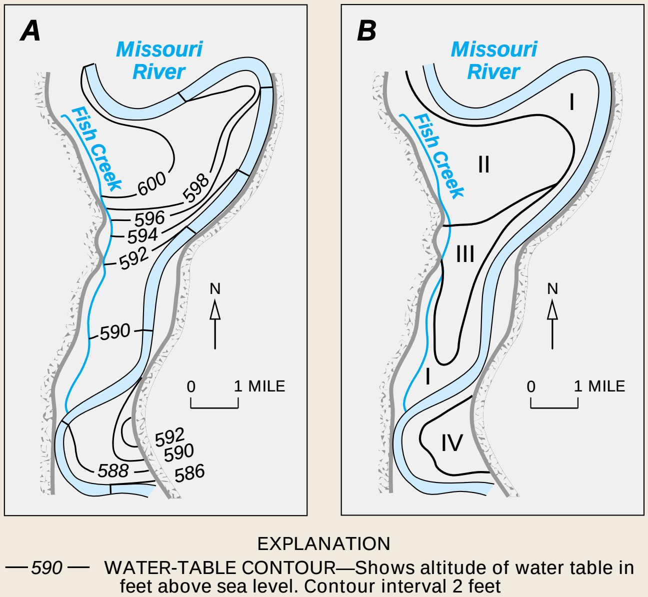


Figure I–2. In flood plains of large rivers, such as the Missouri River near Glasgow, Missouri, patterns of ground-water movement (A) and water-table fluctuations (B) can be complex. Zone I is an area of rapidly fluctuating water levels, zone II is an area of long-term stability, zone III is an area of down-valley flow, and zone IV is a persistent ground-water high. (Modified from Grannemann, N.G., and Sharp, J.M., Jr., 1979, Alluvial hydrogeology of the lower Missouri River: Journal of Hydrology, v. 40, p. 85–99.) (Reprinted with permission from Elsevier Science-NL, Amsterdam, The Netherlands.)

alluvium, it was possible to construct a hydrologic section through the alluvium (Figure I–3), showing that the river receives ground-water discharge from both local and regional ground-water flow systems. In addition, the section also shows the effect of the break in slope associated with the terrace at the edge of the swamp, which causes ground water from a local flow system to discharge into the edge of the swamp rather than to the river.

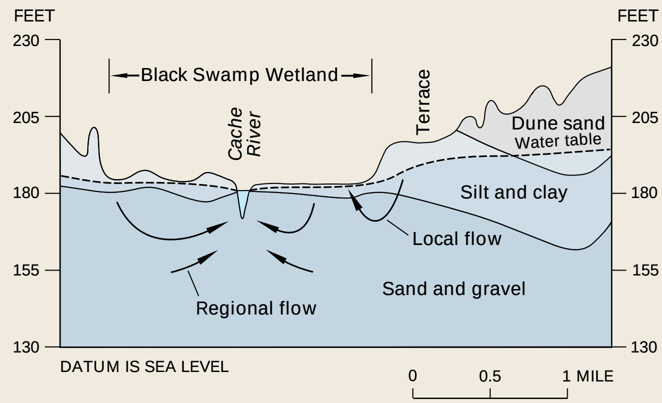


Figure I–3. The Cache River in Arkansas provides an example of contributions to a river from regional and local ground-water flow systems. In addition, a small local ground-water flow system associated with a terrace discharges to the wetland at the edge of the flood plain. (Modified from Gonthier, G.J., 1996, Ground-water flow conditions within a bottomland hardwood wetland, eastern Arkansas: Wetlands, v. 16, no. 3, p. 334–346.) (Used with permission.)

COASTAL TERRAIN

Coastal terrain, such as that along the east-central and southern coasts of the United States, extends from inland scarps and terraces to the ocean (area C of the conceptual landscape, Figure 2). This terrain is characterized by (1) low scarps and terraces that were formed when the ocean was higher than at present; (2) streams, estuaries, and lagoons that are affected by tides; (3) ponds that are commonly associated with coastal sand dunes; and (4) barrier islands. Wetlands cover extensive areas in some coastal terrains (see Figure 18).

The interaction of ground water and surface water in coastal terrain is affected by discharge of ground water from regional flow systems and from local flow systems associated with scarps and terraces (Figure 23), evapotranspiration, and tidal flooding. The local flow systems associated with scarps and terraces are caused by the configuration of the water table near these features (see Box J). Where the water table has a downward break in slope near the top of scarps and terraces, downward components of ground-water flow are present; where the water table has an upward break in slope near the base of these features, upward components of ground-water flow are present.

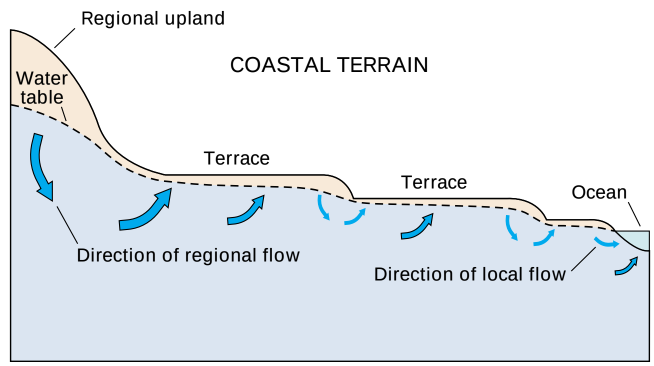
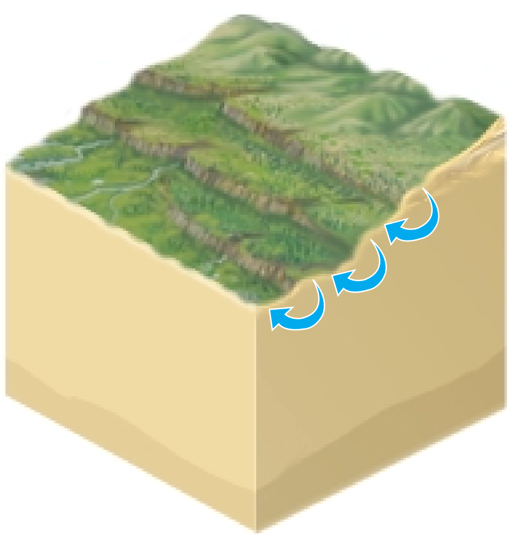


Figure 23. In coastal terrain, small local ground-water flow cells associated with terraces overlie more regional ground-water flow systems. In the tidal zone, saline and brackish surface water mixes with fresh ground water from local and regional flow systems.



Evapotranspiration directly from ground water is widespread in coastal terrain. The land surface is flat and the water table generally is close to land surface; therefore, many plants have root systems deep enough to transpire ground water at nearly the maximum potential rate. The result is that evapotranspiration causes a significant water loss, which affects the configuration of ground-water flow systems as well as how ground water interacts with surface water.

In the parts of coastal landscapes that are affected by tidal flooding, the interaction of ground water and surface water is similar to that in alluvial valleys affected by flooding. The principal difference between the two is that tidal flooding is more predictable in both timing and magnitude than river flooding. The other significant difference is in water chemistry. The water that moves into bank storage from rivers is generally fresh, but the water that moves into bank storage from tides generally is brackish or saline.

Estuaries are a highly dynamic interface between the continents and the ocean, where discharge of freshwater from large rivers mixes with saline water from the ocean. In addition, ground water discharges to estuaries and the ocean, delivering nutrients and contaminants directly to coastal waters. However, few estimates of the location and magnitude of ground-water discharge to coasts have been made.

In some estuaries, sulfate-rich regional ground water mixes with carbonate-rich local ground water and with chloride-rich seawater, creating sharp boundaries that separate plant and wildlife communities. Biological communities associated with these sharp boundaries are adapted to different hydrochemical conditions, and they undergo periodic stresses that result from inputs of water having different chemistry. The balance between river inflow and tides causes estuaries to retain much of the particulate and dissolved matter that is transported in surface and subsurface flows, including contaminants.

“Ground water discharges to estuaries and the ocean, delivering nutrients and contaminants directly to coastal waters”

Field Studies of Coastal Terrain

Along the Atlantic, Gulf of Mexico, and Arctic Coasts of the United States, broad coastal plains are transected by streams, scarps, and terraces. In some parts of these regions, local ground-water flow systems are associated with scarps and terraces, and freshwater wetlands commonly are present. Other parts of coastal regions are affected by tides, resulting in very complex flow and biogeochemical processes.

Underlying the broad coastal plain of the mid-Atlantic United States are sediments 600 or more feet thick. The sands and clays were deposited in stratigraphic layers that slope gently from west to east. Ground water moves regionally toward the east in the more permeable sand layers. These aquifers are separated by discontinuous layers of clay that restrict vertical ground-water movement. Near land surface, local ground-water flow systems are associated with changes in land slope, such as at major scarps and at streams.

Studies of the Dismal Swamp in Virginia and North Carolina provide examples of the interaction of ground water and wetlands near a coastal scarp. The Suffolk Scarp borders the west side of Great Dismal Swamp. Water-table wells and deeper piezometers placed across the scarp indicated a downward component of ground-water flow in the upland and an upward component of ground-water flow in the lowland at the edge of the swamp (Figure J–1*A*). However, at the edge of the swamp the direction of flow changed several times between May and October in 1982 because transpiration of ground water lowered the water table below the water level of the deep piezometer (Figure J–1*B*).

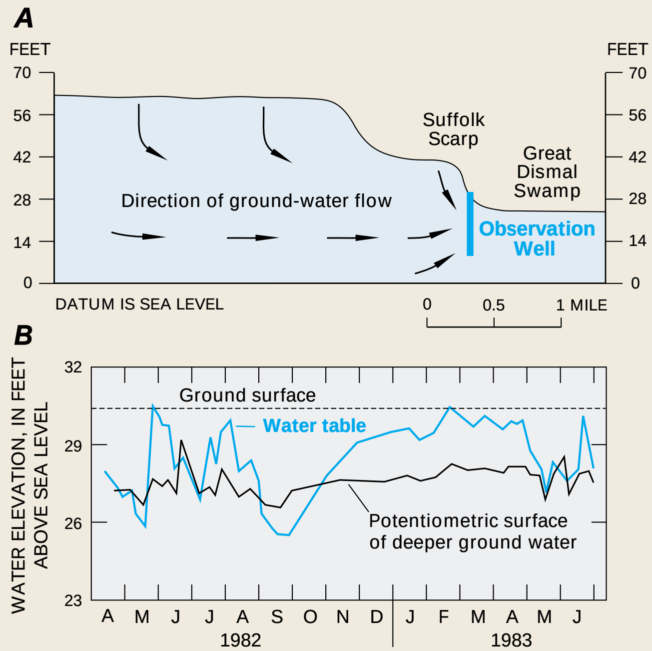
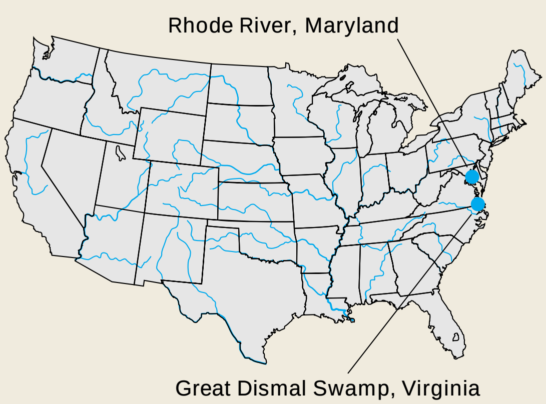


Figure J–1. Ground-water discharge at the edge of the Great Dismal Swamp in Virginia provides an example of local ground-water flow systems associated with coastal scarps (A). The vertical components of flow can change direction seasonally, partly because evapotranspiration discharges shallower ground water during part of the year (B). (Modified from Carter, Virginia, 1990, The Great Dismal Swamp—An illustrated case study, chapter 8, in Lugo, A.E., Brinson, Mark, and Brown, Sandra, eds., Ecosystems of the world, 15: Forested wetlands, Elsevier, Amsterdam, p. 201–211.) (Reprinted with permission from Elsevier Science-NL, Amsterdam, The Netherlands.)



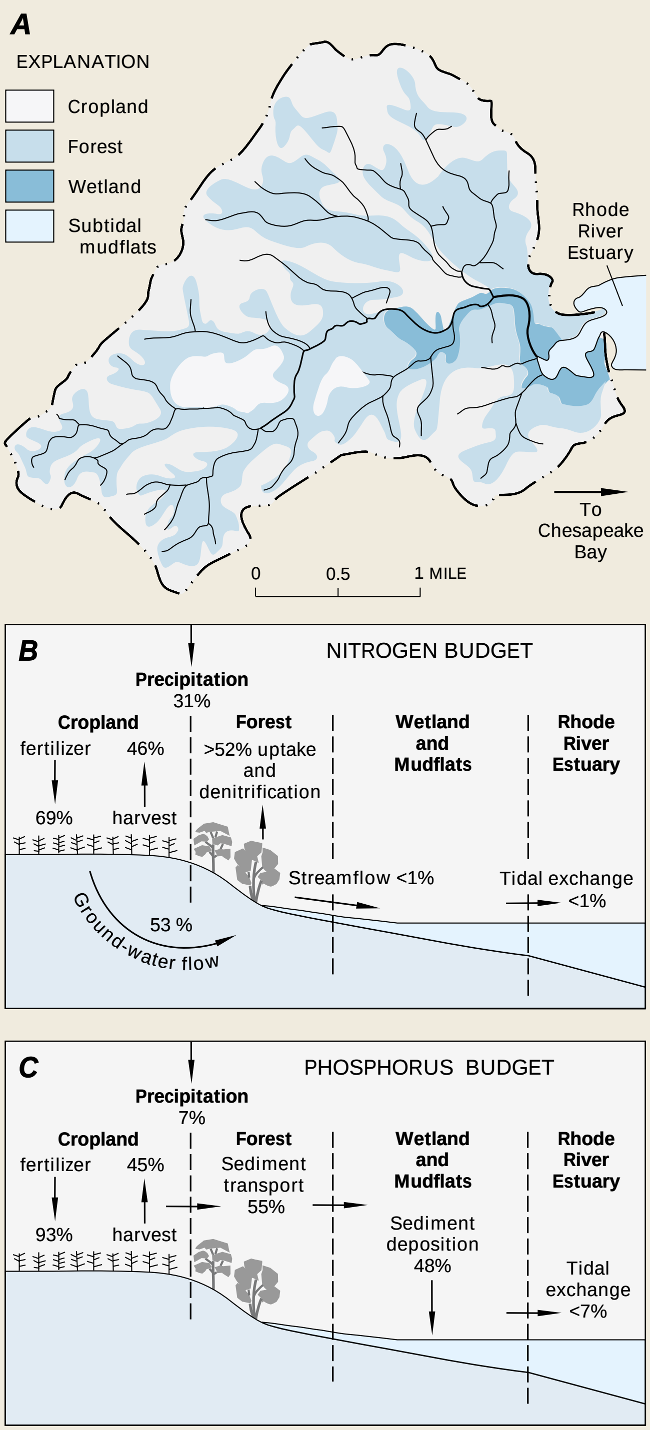


Figure J–2. Forests and wetlands separate cropland from streams in the Rhode River watershed in Maryland (A). More than half of the nitrogen applied to cropland is transported by ground water toward riparian forests and wetlands (B). More than half of the total phosphorus applied to cropland is transported by streams to wetlands and mudflats, where most is deposited in sediments (C). (Modified from Correll, D.L., Jordan, T.E., and Weller, D.E., 1992, Nutrient flux in a landscape—Effects of coastal land use and terrestrial community mosaic on nutrient transport to coastal waters: Estuaries, v. 15, no. 4, p. 431–442.) (Reprinted by permission of the Estuarine Research Federation.)

The gentle relief and sandy, well-drained soils of coastal terrain are ideal for agriculture. Movement of excess nutrients to estuaries are a particular problem in coastal areas because the slow rate of flushing of coastal bays and estuaries can cause them to retain nutrients. At high concentrations, nutrients can cause increased algal production, which results in overabundance of organic matter. This, in turn, can lead to reduction of dissolved oxygen in surface water to the extent that organisms are killed throughout large areas of estuaries and coastal bays.

Movement of nutrients from agricultural fields has been documented for the Rhode River watershed in Maryland (Figure J–2). Application of fertilizer accounts for 69 percent of nitrogen and 93 percent of phosphorus input to this watershed (Figure J–2*B* and J–2*C*). Almost all of the nitrogen that is not removed by harvested crops is transported in ground water and is taken up by trees in riparian forests and wetlands or is denitrified to nitrogen gas in ground water before it reaches streams. On the other hand, most of the phosphorus not removed by harvested crops is attached to soil particles and is transported only during heavy precipitation when sediment from fields is transported into streams and deposited in wetlands and subtidal mudflats at the head of the Rhode River estuary. Whether phosphorus is retained in sediments or is released to the water column depends in part on whether sediments are exposed to oxygen. Thus, the uptake of nutrients and their storage in riparian forests, wetlands, and subtidal mudflats in the Rhode River watershed has helped maintain relatively good water quality in the Rhode River estuary.

In other areas, however, agricultural runoff and input of nutrients have overwhelmed coastal systems, such as in the northern Gulf of Mexico near the mouth of the Mississippi River. The 1993 flood in the Mississippi River system delivered an enormous amount of nutrients to the Gulf of Mexico. Following the flood, oxygen-deficient sediments created areas of black sediment devoid of animal life in parts of the northern Gulf of Mexico.

GLACIAL AND DUNE TERRAIN

Glacial and dune terrain (area G of the conceptual landscape, Figure 2) is characterized by a landscape of hills and depressions. Although stream networks drain parts of these landscapes, many areas of glacial and dune terrain do not contribute runoff to an integrated surface drainage network. Instead, surface runoff from precipitation falling on the landscape accumulates in the depressions, commonly resulting in the presence of lakes and wetlands. Because of the lack of stream outlets, the water balance of these "closed" types of lakes and wetlands is controlled largely by exchange of water with the atmosphere (precipitation and evapotranspiration) and with ground water (see Box K).

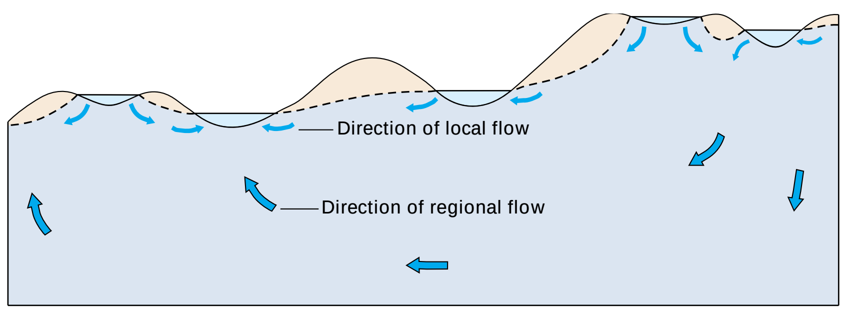
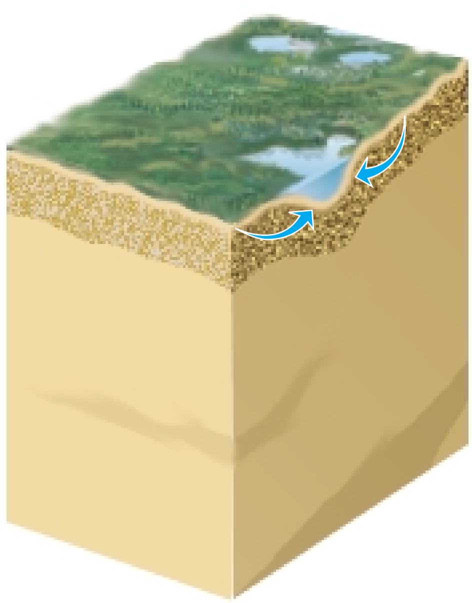


Figure 24. In glacial and dune terrain, local, intermediate, and regional ground-water flow systems interact with lakes and wetlands. It is not uncommon for wetlands that recharge local ground-water flow systems to be present in lowlands and for wetlands that receive discharge from local ground water to be present in uplands.



Lakes and wetlands in glacial and dune terrain can have inflow from ground water, outflow to ground water, or both (Figure 16).
The interaction between lakes and wetlands and ground water is determined to a large extent by their position with respect to local and regional ground-water flow systems. A common conception is that lakes and wetlands that are present in topographically high areas recharge ground water, and that lakes and wetlands that are present in low areas receive discharge from ground water. However, lakes and wetlands underlain by deposits having low permeability can receive discharge from local ground-water flow systems even if they are located in a regional ground-water recharge area. Conversely, they can lose water to local ground-water flow systems even if they are located in a regional ground-water discharge area (Figure 24).

Lakes and wetlands in glacial and dune terrain underlain by highly permeable deposits commonly have ground-water seepage into one side and seepage to ground water on the other side. This relation is relatively stable because the water-table gradient between surface-water bodies in this type of setting is relatively constant. However, the boundary between inflow to the lake or wetland and outflow from it, termed the hinge line, can move up and down along the shoreline. Movement of the hinge line between inflow and outflow is a result of the changing slope of the water table in response to changes in ground-water recharge in the adjacent uplands.

Transpiration directly from ground water has a significant effect on the interaction of lakes and wetlands with ground water in glacial and dune terrain. Transpiration from ground water (Figure 7) has perhaps a greater effect on lakes and wetlands underlain by low-permeability deposits than in any other landscape. The lateral movement of ground water in low-permeability deposits may not be fast enough to supply the quantity of water at the rate it is removed by transpiration, resulting in deep and steep-sided cones of depression. These cones of depression commonly are present around the perimeter of the lakes and wetlands (Figure 7 and Box K).

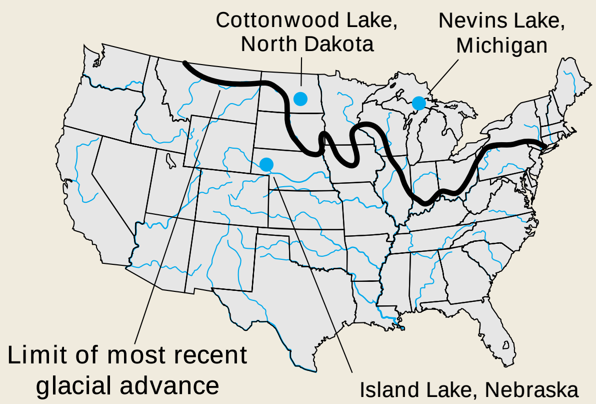
In the north-central United States, cycles in the balance between precipitation and evapotranspiration that range from 5 to 30 years can result in large changes in water levels, chemical concentrations, and major-ion water type of individual wetlands. In some settings, repeated cycling of water between the surface and subsurface in the same locale results in evaporative concentration of solutes and eventually in mineral precipitation in the subsurface. In addition, these dynamic hydrological and chemical conditions can cause significant changes in the types, number, and distribution of wetland plants and invertebrate animals within wetlands. These changing hydrological conditions that range from seasons to decades are an essential process for rejuvenating wetlands that provide ideal habitat and feeding conditions for migratory waterfowl.

"The hydrological and chemical characteristics of lakes and wetlands in glacial and dune terrain are determined to a large extent by their position with respect to local and regional ground-water flow systems"

Field Studies of Glacial and Dune Terrain

Glacial terrain and dune terrain are characterized by land-surface depressions, many of which contain lakes and wetlands. Although much of the glacial terrain covering the north-central United States (see index map) has low topographic relief, neighboring lakes and wetlands are present at a sufficiently wide range of altitudes to result in many variations in how they interact with ground water, as evidenced by the following examples.

The Cottonwood Lake area, near Jamestown, North Dakota, is within the prairie-pothole region of North America. The hydrologic functions of these small depressional wetlands are highly variable in space and time. With respect to spatial variation, some wetlands recharge ground water, some receive ground-water inflow and have outflow to ground water, and some receive ground-water discharge. Wetland P1 provides an example of how their functions can vary in time. The wetland receives ground-water discharge most of the time; however, transpiration of ground water by plants around the perimeter of the wetland can cause water to seep from the wetland. Seepage from wetlands commonly is assumed to be ground-water recharge, but in cases like Wetland P1, the water is actually lost to transpiration. This process results in depressions in the water table around the perimeter of the wetland at certain times, as shown in



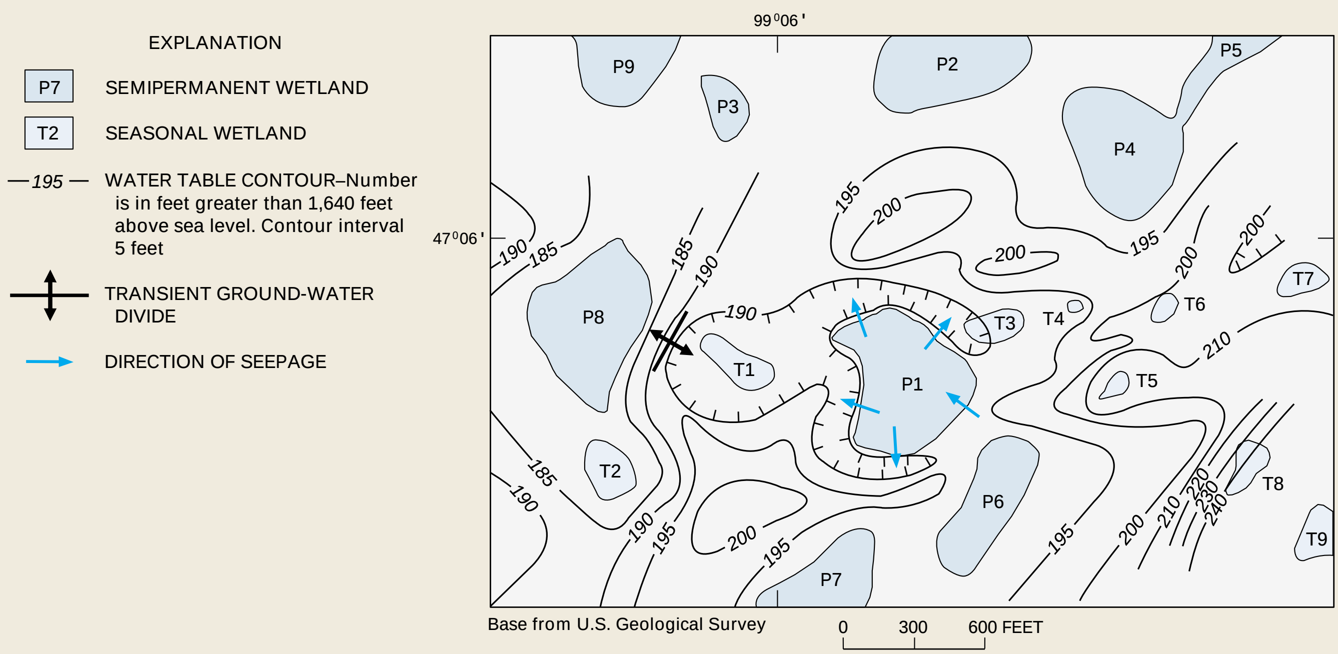


Figure K–1. Transpiration directly from ground water causes cones of depression to form by late summer around the perimeter of prairie pothole Wetland P1 in the Cottonwood Lake area in North Dakota. (Modified from Winter, T.C., and Rosenberry, D.O., 1995, The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979–1990: Wetlands, v. 15, no. 3, p. 193–211.) (Used with permission.)

Figure K–1. Transpiration-induced depressions in the water table commonly are filled in by recharge during the following spring, but then form again to some extent by late summer nearly every year.

Nevins Lake, a closed lake in the Upper Peninsula of Michigan, illustrates yet another type of interaction of lakes with ground water in glacial terrain. Water-chemistry studies of Nevins Lake indicated that solutes such as calcium provide an indicator of ground-water inflow to the lake. Immediately following spring snowmelt, the mass of dissolved calcium in the lake increased rapidly because of increased ground-water inflow. Calcium then decreased steadily throughout the summer and early fall as the lake received less ground-water inflow (Figure K–2). This pattern varied annually depending on the amount of ground-water recharge from snowmelt and spring rains. The chemistry of water in the pores of the lake sediments was used to determine the spatial variability in the direction of seepage on the side of the lake that had the most ground-water inflow. Seepage was always out of the lake at the sampling site farthest from shore and was always upward into the lake at the site nearest to shore. Flow reversals were documented at sites located at intermediate distances from shore.

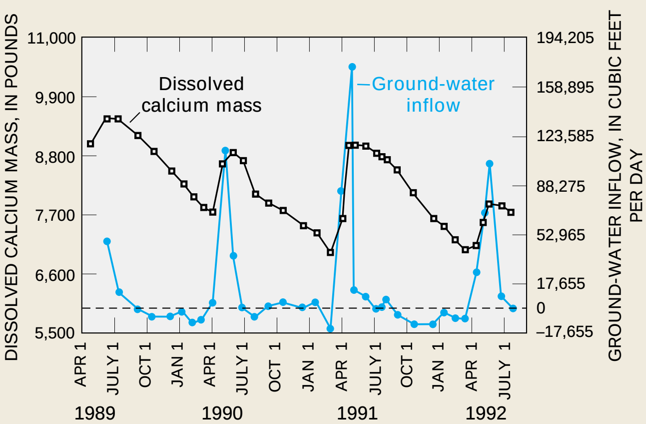


Figure K–2. A large input of ground water during spring supplies the annual input of calcium to Nevins Lake in the Upper Peninsula of Michigan. (Modified from Krabbenhoft, D.P., and Webster, K.E., 1995, Transient hydrogeological controls on the chemistry of a seepage lake: Water Resources Research, v. 31, no. 9, p. 2295–2305.)

Dune terrain also commonly contains lakes and wetlands. Much of the central part of western Nebraska, for example, is covered by sand dunes that have lakes and wetlands in most of the lowlands between the dunes. Studies of the interaction of lakes and wetlands with ground water at the Crescent Lake National Wildlife Refuge indicate that most of these lakes have seepage inflow from ground water and seepage outflow to ground water. The chemistry of inflowing ground water commonly has an effect on lake water chemistry. However, the chemistry of lake water can also affect ground water in areas of seepage from lakes. In the Crescent Lake area, for example, plumes of lake water were detected in ground water downgradient from the lakes, as indicated by the plume of dissolved organic carbon downgradient from Roundup Lake and Island Lake (Figure K–3).

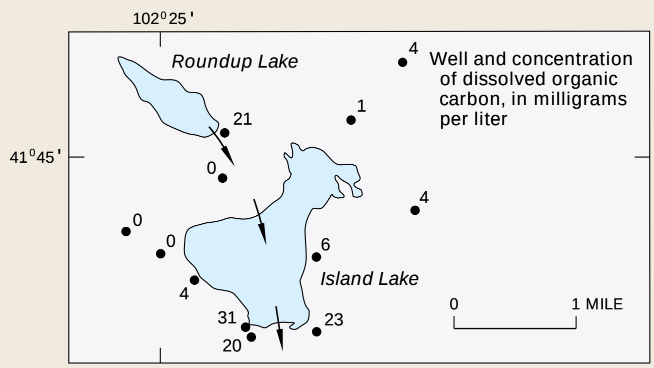
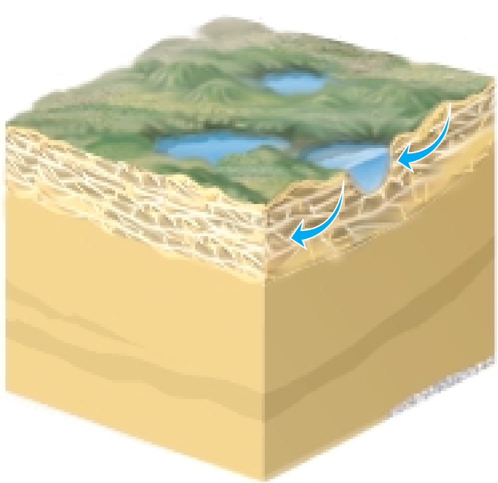


Figure K–3. Seepage from lakes in the sandhills of Nebraska causes plumes of dissolved organic carbon to be present in ground water on the downgradient sides of the lakes. (Modified from LaBaugh, J.W., 1986, Limnological characteristics of selected lakes in the Nebraska sandhills, U.S.A., and their relation to chemical characteristics of adjacent ground water: Journal of Hydrology, v. 86, p. 279–298.) (Reprinted with permission of Elsevier Science-NL, Amsterdam, The Netherlands.)

KARST TERRAIN

Karst may be broadly defined as all landforms that are produced primarily by the dissolution of rocks, mainly limestone and dolomite. Karst terrains (area K of the conceptual landscape, Figure 2) are characterized by (1) closed surface depressions of various sizes and shapes known as sinkholes, (2) an underground drainage network that consists of solution openings that range in size from enlarged cracks in the rock to large caves, and (3) highly disrupted surface drainage systems, which relate directly to the unique character of the underground drainage system.

Dissolution of limestone and dolomite guides the initial development of fractures into solution holes that are diagnostic of karst terrain. Perhaps nowhere else is the complex interplay between hydrology and chemistry so important to changes in landform. Limestone and dolomite weather quickly, producing calcium and magnesium carbonate waters that are relatively high in ionic strength. The increasing size of solution holes allows higher ground-water flow rates across a greater surface area of exposed minerals, which stimulates the dissolution process further, eventually leading to development of caves. Development of karst terrain also involves biological processes. Microbial production of carbon dioxide in the soil affects the carbonate equilibrium of water as it recharges ground water, which then affects how much mineral dissolution will take place before solute equilibrium is reached.



Ground-water recharge is very efficient in karst terrain because precipitation readily infiltrates through the rock openings that intersect the land surface. Water moves at greatly different rates through karst aquifers; it moves slowly through fine fractures and pores and rapidly through solution-enlarged fractures and conduits. As a result, the water discharging from many springs in karst terrain may be a combination of relatively slow-moving water draining from pores and rapidly moving storm-derived water. The slow-moving component tends to reflect the chemistry of the aquifer materials, and the more rapidly moving water associated with recent rainfall tends to reflect the chemical characteristics of precipitation and surface runoff.

Water movement in karst terrain is especially unpredictable because of the many paths ground water takes through the maze of fractures and solution openings in the rock (see Box L). Because of the large size of interconnected openings in well-developed karst systems, karst terrain can have true underground streams. These underground streams can have high rates of flow, in some places as great as rates of flow in surface streams. Furthermore, it is not unusual for medium-sized streams to disappear into the rock openings, thereby completely disrupting the surface drainage system, and to reappear at the surface at another place. Seeps and springs of all sizes are characteristic features of karst terrains. Springs having sufficiently large ground-water recharge areas commonly are the source of small- to medium-sized streams and constitute a large part of tributary flow to larger streams. In addition, the location where the streams emerge can change, depending on the spatial distribution of ground-water recharge in relation to individual precipitation events. Large spring inflows to streams in karst terrain contrast sharply with the generally more diffuse ground-water inflow characteristic of streams flowing across sand and gravel aquifers.

Because of the complex patterns of surface-water and ground-water flow in karst terrain, many studies have shown that surface-water drainage divides and ground-water drainage divides do not coincide. An extreme example is a stream that disappears in one surface-water basin and reappears in another basin. This situation complicates the identification of source areas for water and associated dissolved constituents, including contaminants, in karst terrain.

Water chemistry is widely used for studying the hydrology of karst aquifers. Extensive tracer studies (see Box G) and field mapping to locate points of recharge and discharge have been used to estimate the recharge areas of springs, rates of ground-water movement, and the water balance of aquifers. Variations in parameters such as temperature, hardness, calcium/magnesium ratios, and other chemical characteristics have been used to identify areas of ground-water recharge, differentiate rapid- and slow-moving ground-water flow paths, and compare springflow characteristics in different regions. Rapid transport of contaminants within karst aquifers and to springs has been documented in many locations. Because of the rapid movement of water in karst aquifers, water-quality problems that might be localized in other aquifer systems can become regional problems in karst systems.

Some landscapes considered to be karst terrain do not have carbonate rocks at the land surface. For example, in some areas of the southeastern United States, surficial deposits overlie carbonate rocks, resulting in a “mantled” karst terrain. Lakes and wetlands in mantled karst terrain interact with shallow ground water in a manner similar to that in sandy glacial and dune terrains. The difference between how lakes and wetlands interact with ground water in sandy glacial and dune terrain and how they interact in the mantled karst is related to the buried carbonate rocks. If dissolution of the buried carbonate rocks causes slumpage of an overlying confining bed, such that water can move freely through the confining bed, the lakes and wetlands also can be affected by changing hydraulic heads in the aquifers underlying the confining bed (see Box L).

Field Studies of Karst Terrain

Karst terrain is characteristic of regions that are underlain by limestone and dolomite bedrock. In many karst areas, the carbonate bedrock is present at land surface, but in other areas it may be covered by other deposits and is referred to as “mantled” karst. The Edwards Aquifer in south-central Texas is an example of karst terrain where the limestones and dolomites are exposed at land surface (Figure L–1). In this outcrop area, numerous solution cavities along vertical joints and sinkholes provide an efficient link between the land surface and the water table. Precipitation on the outcrop area tends to infiltrate rapidly into the ground, recharging ground water. In addition, a considerable amount of recharge to the aquifer is provided by losing streams that cross the outcrop area. Even the largest streams that originate to the north are dry in the outcrop area for most of the year. The unusual highway signs in this area go beyond local pride in a prolific water supply—they reflect a clear understanding of how vulnerable this water supply is to contamination by human activities at the land surface.

Just as solution cavities are major avenues for ground-water recharge, they also are focal points for ground-water discharge from karst aquifers. For example, springs near the margin of the Edwards Aquifer provide a continuous source of water for streams to the south.

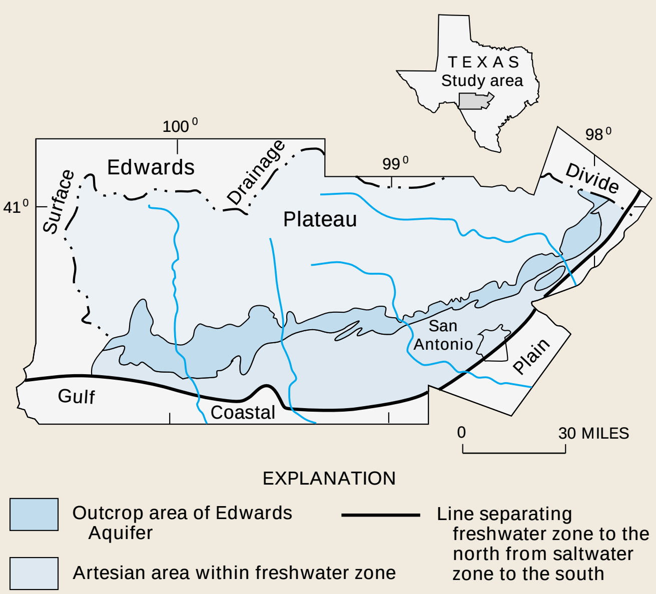
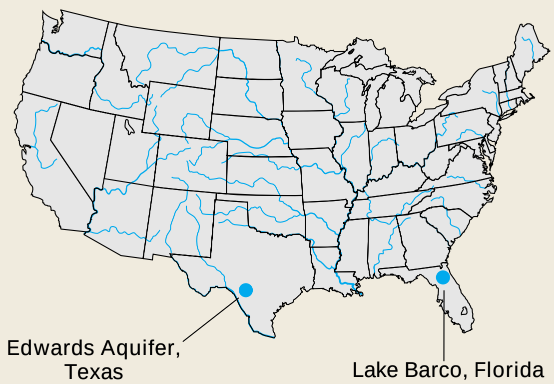


Figure L–1. A large area of karst terrain is associated with the Edwards Aquifer in south-central Texas. Large streams lose a considerable amount of water to ground water as they traverse the outcrop area of the Edwards Aquifer. (Modified from Brown, D.S., and Patton, J.T., 1995, Recharge to and discharge from the Edwards Aquifer in the San Antonio area, Texas, 1995: U.S. Geological Survey Open-File Report 96–181, 2 p.)

An example of mantled karst can be found in north-central Florida, a region that has many sinkhole lakes. In this region, unconsolidated deposits overlie the highly soluble limestone of the Upper Floridan aquifer. Most land-surface depressions containing lakes in Florida are formed when unconsolidated surficial deposits slump into sinkholes that form in the underlying limestone. Thus, although the lakes are not situated directly in limestone, the sinkholes in the bedrock underlying lakes commonly have a significant effect on the hydrology of the lakes.



Lake Barco is one of numerous lakes occupying depressions in northern Florida. Results of a study of the interaction of Lake Barco with ground water indicated that shallow ground water flows into the northern and northeastern parts of the lake, and lake water seeps out to shallow ground water in the western and southern parts (Figure L–2*A*). In addition, ground-water flow is downward beneath most of Lake Barco (Figure L–2*B*).

The studies of lake and ground-water chemistry included the use of tritium, chlorofluorocarbons (CFCs), and isotopes of oxygen (see Box G). The results indicated significant differences in the chemistry of (1) shallow ground water flowing into Lake Barco, (2) Lake Barco water, (3) shallow ground water downgradient from Lake Barco, and (4) deeper ground water beneath Lake Barco. Oxygen-rich lake water moving through the organic-rich lake sediments is reduced, resulting in discharge of oxygen-depleted water into the ground water beneath Lake Barco. This downward-moving ground water may have an undesired effect on the chemical quality of ground water in the underlying Upper Floridan aquifer, which is the principal source of water supply for the region. The patterns of ground-water movement determined from hydraulic-head data were corroborated by chemical tracers. For example, the dates that ground water in different parts of the flow system was recharged, as determined from CFC dating, show a fairly consistent increase in the length of time since recharge with depth (Figure L–2*C*).

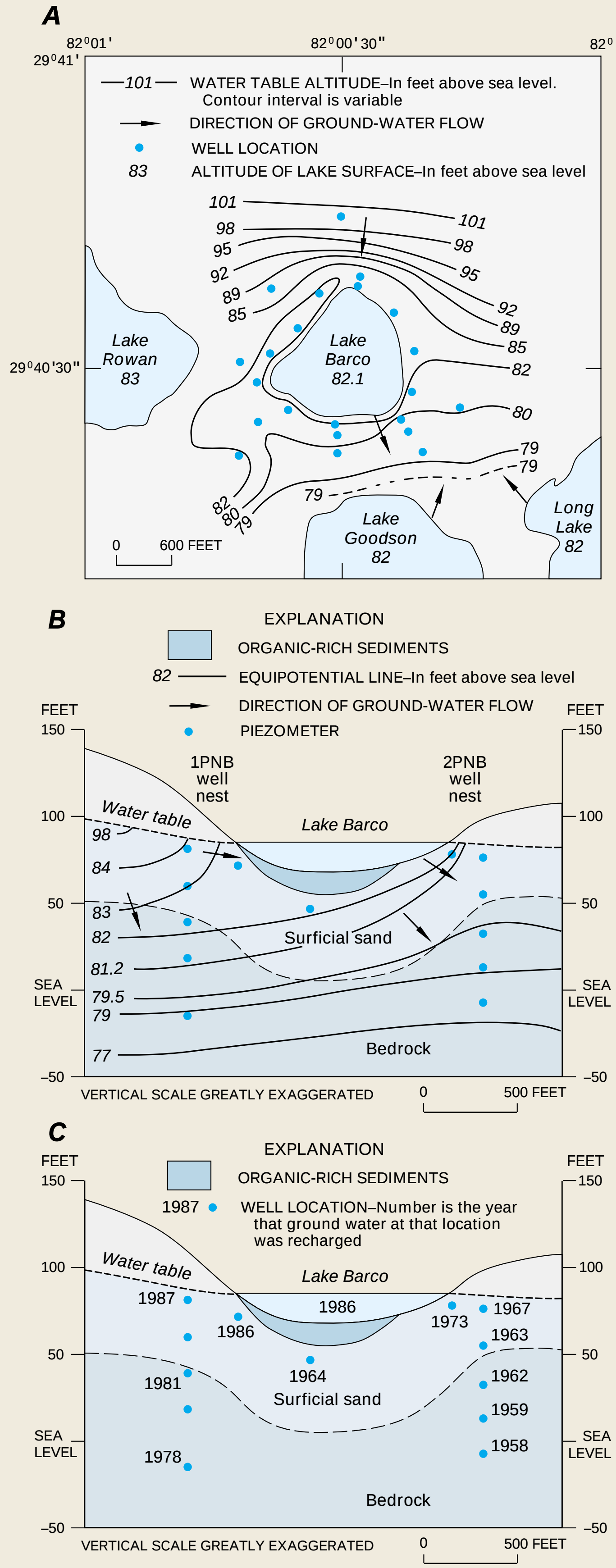


Figure L–2. Lake Barco, in northern Florida, is a flow-through lake with respect to ground water (A and B). The dates that ground water in different parts of the ground-water system was recharged indicate how long it takes water to move from the lake or water table to a given depth (C). (Modified from Katz, B.G., Lee, T.M., Plummer, L.N., and Busenberg, E., 1995, Chemical evolution of groundwater near a sinkhole lake, northern Florida, 1. Flow patterns, age of groundwater, and influence of lake water leakage: Water Resources Research, v. 31, no. 6, p. 1549–1564.)

EFFECTS OF HUMAN ACTIVITIES ON THE INTERACTION OF GROUND WATER AND SURFACE WATER

Human activities commonly affect the distribution, quantity, and chemical quality of water resources. The range in human activities that affect the interaction of ground water and surface water is broad. The following discussion does not provide an exhaustive survey of all human effects but emphasizes those that are relatively widespread. To provide an indication of the extent to which humans affect the water resources of virtually all landscapes, some of the most relevant structures and features related to human activities are superimposed on various parts of the conceptual landscape (Figure 25).

The effects of human activities on the quantity and quality of water resources are felt over a wide range of space and time scales. In the following discussion, "short term" implies time scales from hours to a few weeks or months, and "long term" may range from years to decades. "Local scale" implies distances from a few feet to a few thousand feet and areas as large as a few square miles, and "subregional and regional scales" range from tens to thousands of square miles. The terms point source and nonpoint source with respect to discussions of contamination are used often; therefore, a brief discussion of the meaning of these terms is presented in Box M.

Agricultural Development

Agriculture has been the cause of significant modification of landscapes throughout the world. Tillage of land changes the infiltration and runoff characteristics of the land surface, which affects recharge to ground water, delivery of water and sediment to surface-water bodies, and evapotranspiration. All of these processes either directly or indirectly affect the interaction of ground water and surface water. Agriculturalists are aware of the substantial negative effects of agriculture on water resources and have developed methods to alleviate some of these effects. For example, tillage practices have been modified to maximize retention of water in soils and to minimize erosion of soil from the land into surface-water bodies. Two activities related to agriculture that are particularly relevant to the interaction of ground water and surface water are irrigation and application of chemicals to cropland.

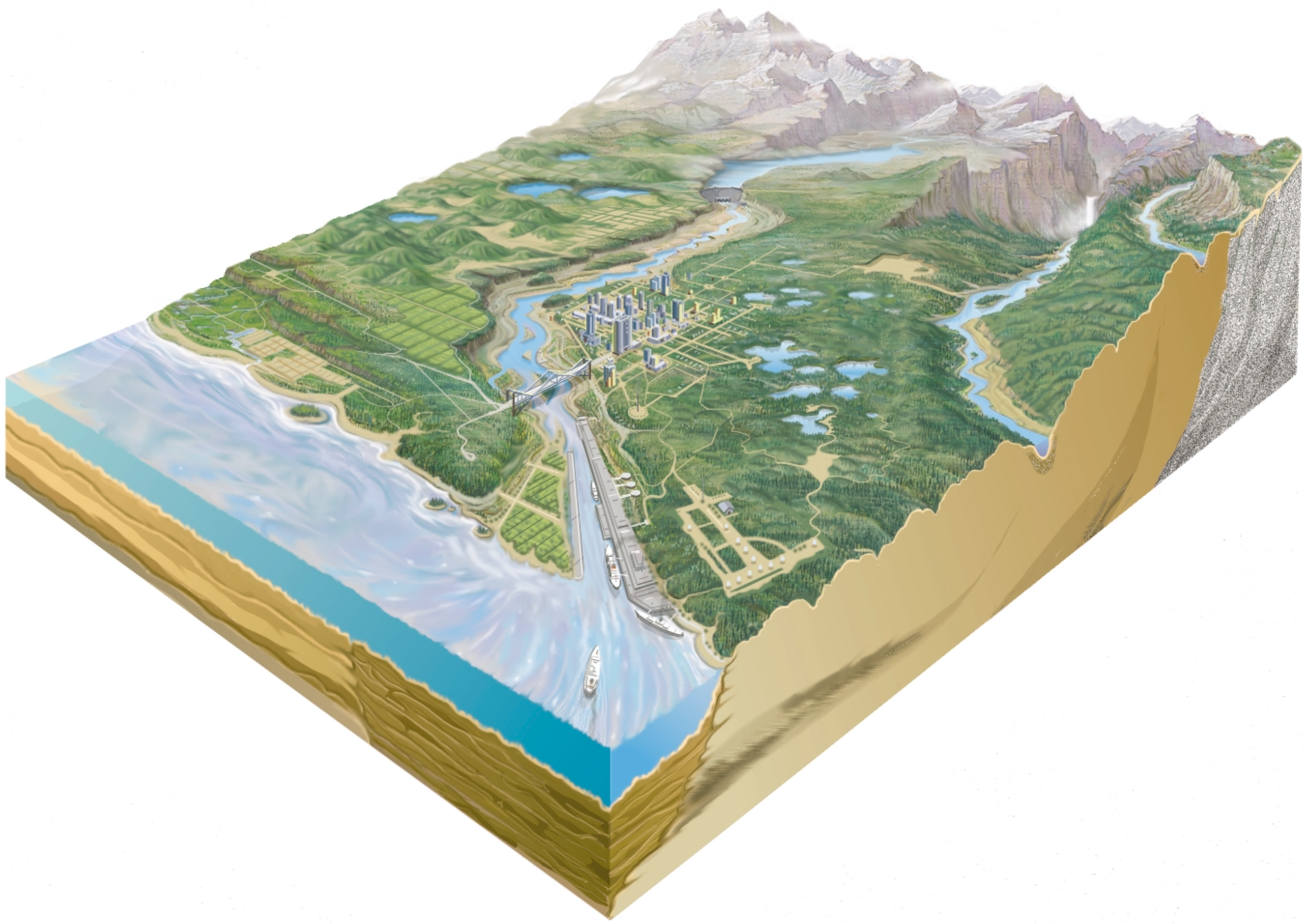


Figure ***25.*** *Human activities and structures, as depicted by the distribution of various examples in the conceptual landscape, affect the interaction of ground water and surface water in all types of landscapes.*

M

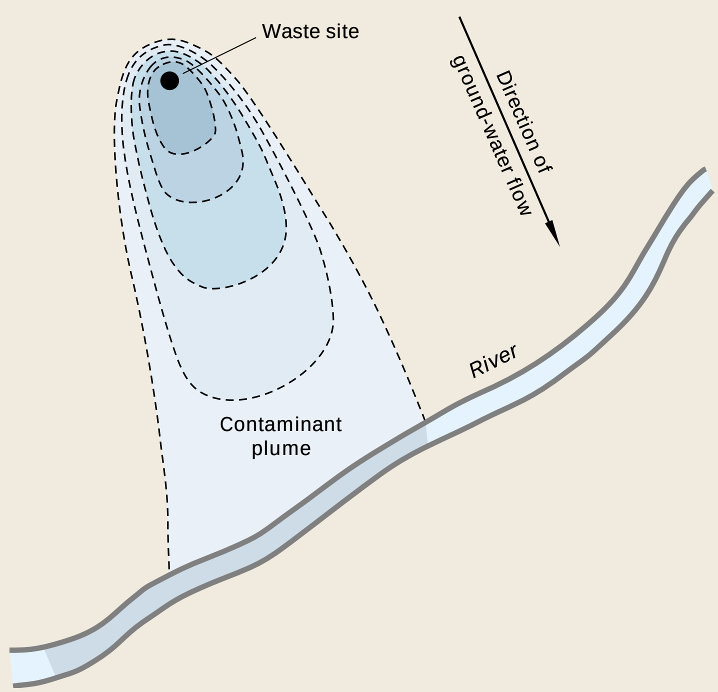
Point and Nonpoint Sources of Contaminants

Contaminants may be present in water or in air as a result of natural processes or through mechanisms of displacement and dispersal related to human activities. Contaminants from point sources discharge either into ground water or surface water through an area that is small relative to the area or volume of the receiving water body. Examples of point sources include discharge from sewage-treatment plants, leakage from gasoline storage tanks, and seepage from landfills (Figure M–1).

Nonpoint sources of contaminants introduce contaminants to the environment across areas that are large compared to point sources, or nonpoint sources may consist of multiple, closely spaced point sources. A nonpoint source of contamination that can be present anywhere, and affect large areas, is deposition from the atmosphere, both by precipitation (wet deposition) or by dry fallout (dry deposition). Agricultural fields, in aggregate, represent large areas through which fertilizers and pesticides can be released to the environment.

The differentiation between point and nonpoint sources of contamination is arbitrary to some extent and may depend in part on the scale at which a problem is considered. For example, emissions from a single smokestack is a point source, but these emissions may be meaningless in a regional analysis of air pollution. However, a fairly even distribution of tens or hundreds of smokestacks might be considered as a nonpoint source. As another example, houses in suburban areas that do not have a combined sewer system have individual septic tanks. At the local scale, each septic tank may be considered as point source of contamination to shallow ground water. At the regional scale, however, the combined contamination of ground water from all the septic tanks in a suburban area may be considered a nonpoint source of contamination to a surface-water body.

Figure M–1. The transport of contamination from a point source by ground water can cause contamination of surface water, as well as extensive contamination of ground water.



IRRIGATION SYSTEMS

Surface-water irrigation systems represent some of the largest integrated engineering works undertaken by humans. The number of these systems greatly increased in the western United States in the late 1840s. In addition to dams on streams, surface-water irrigation systems include (1) a complex network of canals of varying size and carrying capacity that transport water, in many cases for a considerable distance, from a surface-water source to individual fields, and (2) a drainage system to carry away water not used by plants that may be as extensive and complex as the supply system. The drainage system may include underground tile drains. Many irrigation systems that initially used only surface water now also use ground water. The pumped ground water commonly is used directly as irrigation water, but in some cases the water is distributed through the system of canals.

Average quantities of applied water range from several inches to 20 or more inches of water per year, depending on local conditions, over the entire area of crops. In many irrigated areas, about 75 to 85 percent of the applied water is lost to evapotranspiration and retained in the crops (referred to as consumptive use). The remainder of the water either infiltrates through the soil zone to recharge ground water or it returns to a local surface-water body through the drainage system (referred to as irrigation return flow). The quantity of irrigation water that recharges ground water usually is large relative to recharge from precipitation because large irrigation systems commonly are in regions of low precipitation and low natural recharge. As a result, this large volume of artificial recharge can cause the water table to rise (see Box N), possibly reaching the land surface in some areas and waterlogging the fields. For this reason, drainage systems that maintain the level of the water table below the root zone of the crops, generally 4 to 5 feet below the land surface, are an essential component of some irrigation systems. The permanent rise in the water table that is maintained by continued recharge from irrigation return flow commonly results in an increased outflow of shallow ground water to surface-water bodies downgradient from the irrigated area.

N

Effects of Irrigation Development on the Interaction of Ground Water and Surface Water

Nebraska ranks second among the States with respect to the area of irrigated acreage and the quantity of water used for irrigation. The irrigation water is derived from extensive supply systems that use both surface water and ground water (Figure N–1). Hydrologic conditions in different parts of Nebraska provide a number of examples of the broad-scale effects of irrigation development on the interactions of ground water and surface water. As would be expected, irrigation systems based on surface water are always located near streams. In general, these streams are perennial and (or) have significant flow for at least part of the year. In contrast, irrigation systems based on ground water can be located nearly anywhere that has an adequate ground-water resource. Areas of significant rise and decline in ground-water levels due to irrigation systems are shown in Figure N–2. Ground-water levels rise in some areas irrigated with surface water and decline in some areas irrigated with ground water. Rises in ground-water levels near streams result in increased ground-water inflow to gaining streams or decreased flow from the stream to ground water for losing streams. In some areas, it is possible that a stream that was losing water before development of irrigation could become a gaining stream following irrigation. This effect of surface-water irrigation probably caused the rises in ground-water levels in areas F and G in south-central Nebraska (Figure N–2).

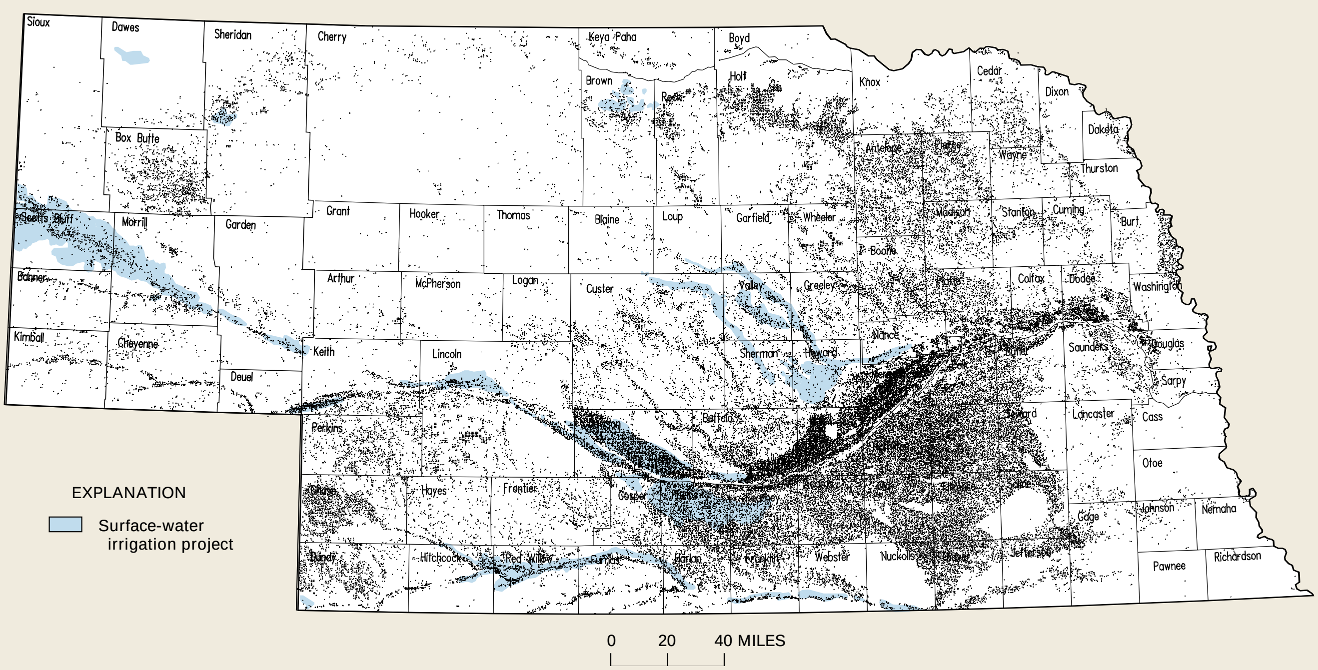


Figure N–1. Nebraska is one of the most extensively irrigated States in the Nation. The irrigation water comes from both ground-water and surface-water sources. Dots are irrigation wells. (Map provided by the University of Nebraska, Conservation and Survey Division.)

Average annual precipitation ranges from less than 15 inches in western Nebraska to more than 30 inches in eastern Nebraska. A large concentration of irrigation wells is present in area E (Figure N–2). The ground-water withdrawals by these wells caused declines in ground-water levels that could not be offset by recharge from precipitation and the presence of nearby flowing streams. In this area, the withdrawals cause decreases in ground-water discharge to the streams and (or) induce flow from the streams to shallow ground water. In contrast, the density of irrigation wells in areas A, B, and C is less than in area E, but water-level declines in these three western areas are similar to area E. The similar decline caused by fewer wells in the west compared to the east is related to less precipitation, less ground-water recharge, and less streamflow available for seepage to ground water.

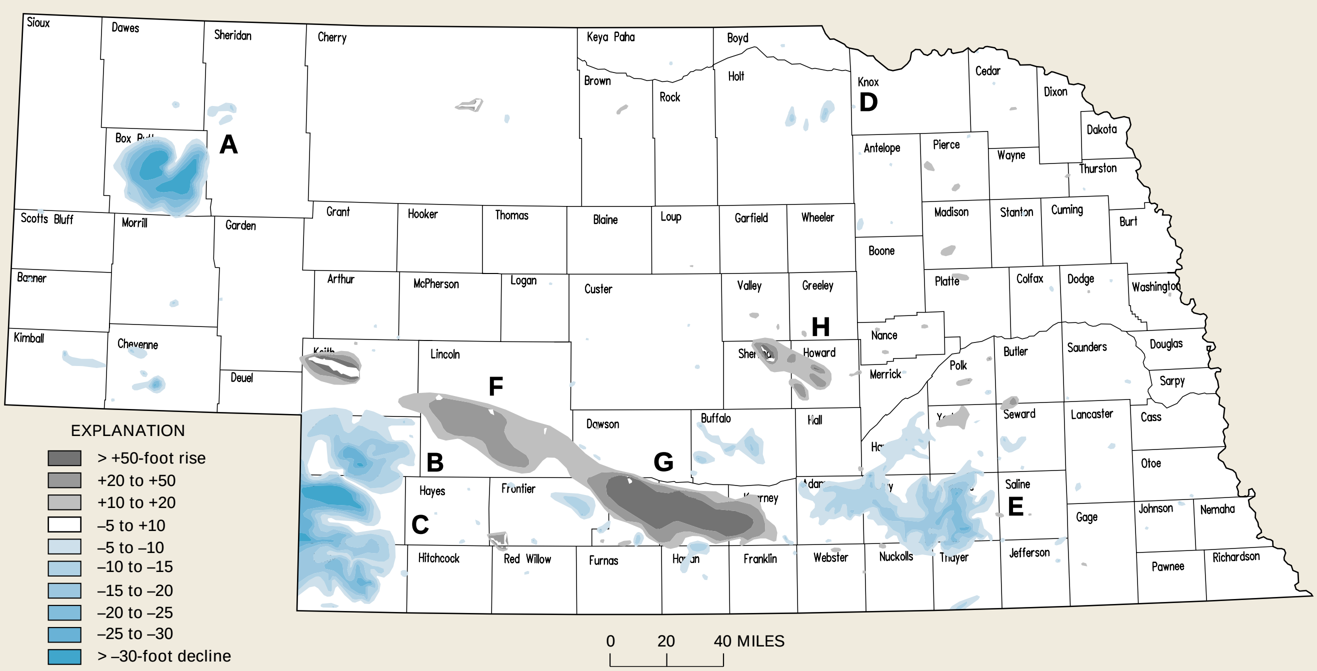


Figure N–2. The use of both ground water and surface water for irrigation in Nebraska has resulted in significant rises and declines of ground-water levels in different parts of the State. (Map provided by the University of Nebraska, Conservation and Survey Division.)

Although early irrigation systems made use of surface water, the development of large-scale sprinkler systems in recent decades has greatly increased the use of ground water for irrigation for several reasons: (1) A system of supply canals is not needed, (2) ground water may be more readily available than surface water, and (3) many types of sprinkler systems can be used on irregular land surfaces; the fields do not have to be as flat as they do for gravity-flow, surface-water irrigation. Whether ground water or surface water was used first to irrigate land, it was not long before water managers recognized that development of either water resource could affect the other. This is particularly true in many alluvial aquifers in arid regions where much of the irrigated land is in valleys.

Significant changes in water quality accompany the movement of water through agricultural fields. The water lost to evapotranspiration is relatively pure; therefore, the chemicals that are left behind precipitate as salts and accumulate in the soil zone. These continue to increase as irrigation continues, resulting in the dissolved-solids concentration in the irrigation return flows being significantly higher in some areas than that in the original irrigation water. To prevent excessive buildup of salts in the soil, irrigation water in excess of the needs of the crops is required to dissolve and flush out the salts and transport them to the ground-water system. Where these dissolved solids reach high concentrations, the artificial recharge from irrigation return flow can result in degradation of the quality of ground water and, ultimately, the surface water into which the ground water discharges.

“Whether ground water or surface water was used first to irrigate land, it was not long before water managers recognized that development of either water resource could affect the other”

USE OF AGRICULTURAL CHEMICALS

Applications of pesticides and fertilizers to cropland can result in significant additions of contaminants to water resources. Some pesticides are only slightly soluble in water and may attach (sorb) to soil particles instead of remaining in solution; these compounds are less likely to cause contamination of ground water. Other pesticides, however, are detected in low, but significant, concentrations in both ground water and surface water. Ammonium, a major component of fertilizer and manure, is very soluble in water, and increased concentrations of nitrate that result from nitrification of ammonium commonly are present in both ground water and surface water associated with agricultural lands (see Box O). In addition to these nonpoint sources of water contamination, point sources of contamination are common in agricultural areas where livestock are concentrated in small areas, such as feedlots. Whether the initial contamination is present in ground water or surface water is somewhat immaterial because the close interaction of the two sometimes results in both being contaminated (see Box P).

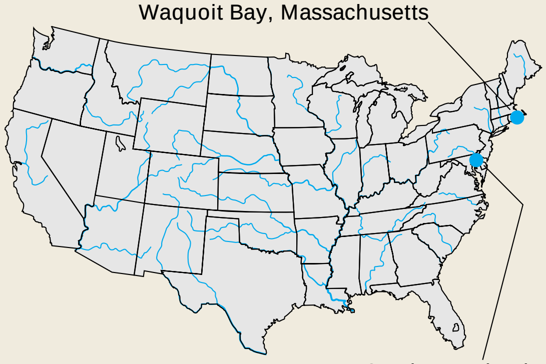
"Whether the initial contamination is present in ground water or surface water is somewhat immaterial because the close interaction of the two sometimes results in both being contaminated"

O

Effects of Nitrogen Use on the Quality of Ground Water and Surface Water

Nitrate contamination of ground water and surface water in the United States is widespread because nitrate is very mobile in the environment. Nitrate concentrations are increasing in much of the Nation's water, but they are particularly high in ground water in the midcontinent region of the United States. Two principal chemical reactions are important to the fate of nitrogen in water: (1) fertilizer ammonium can be nitrified to form nitrate, which is very mobile as a dissolved constituent in shallow ground water, and (2) nitrate can be denitrified to produce nitrogen gas in the presence of chemically reducing conditions if a source of dissolved organic carbon is available.

High concentrations of nitrate can contribute to excessive growth of aquatic plants, depletion of oxygen, fishkills, and general degradation of aquatic habitats. For example, a study of Waquoit Bay in Massachusetts linked the decline in eelgrass beds since 1950 to a progressive increase in nitrate input due to expansion of domestic septic-field developments in the drainage basin (Figure O–1). Loss of eelgrass is a concern because this aquatic plant stabilizes sediment and provides ideal habitat for juvenile fish and other fauna in coastal bays and estuaries. Larger nitrate concentrations supported algal growth that caused turbidity and shading, which contributed to the decline of eelgrass.



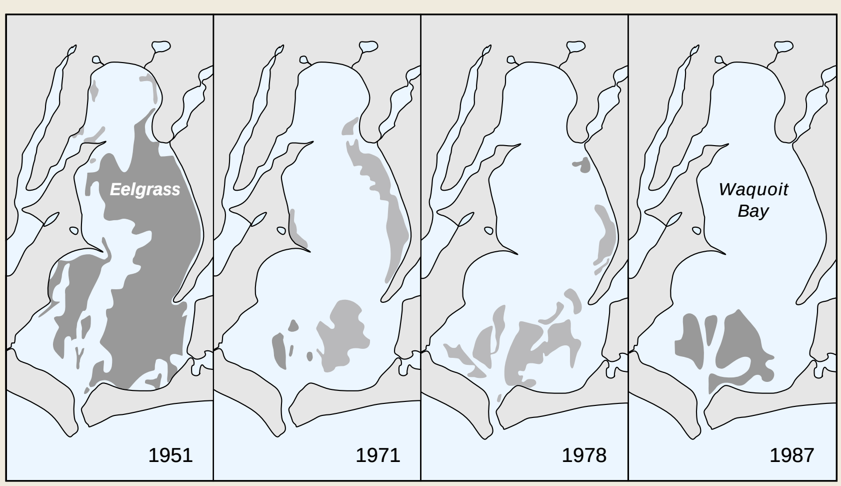


Figure O–1. The areal extent of eelgrass in Waquoit Bay, Massachusetts, decreased markedly between 1951 and 1987 because of increased inputs of nitrogen related to domestic septic-field developments. (Modified from Valiela, I., Foreman, K., LaMontagne, M., Hersh, D., Costa, J., Peckol, P., DeMeo-Andeson, B., D'Avanzo, C., Babione, M., Sham, C.H., Brawley, J., and Lajtha, K., 1992, Couplings of watersheds and coastal waters—Sources and consequences of nutrient enrichment in Waquoit Bay, Massachusetts: Estuaries, v. 15, no. 4, p. 433–457.) (Reprinted by permission of the Estuarine Research Federation.)

Significant denitrification has been found to take place at locations where oxygen is absent or present at very low concentrations and where suitable electron-donor compounds, such as organic carbon, are available. Such locations include the interface of aquifers with silt and clay confining beds and along riparian zones adjacent to streams. For example, in a study on the eastern shore of Maryland, nitrogen isotopes and other environmental tracers were used to show that the degree of denitrification that took place depended on the extent of interaction between ground-water and the chemically reducing sediments near or below the bottom of the Aquia Formation. Two drainage basins were studied: Morgan Creek and Chesterville Branch (Figure O–2). Ground-water discharging beneath both streams had similar nitrate concentration when recharged. Significant denitrification took place in the Morgan Creek basin where a large fraction of local ground-water flow passed through the reducing sediments, which are present at shallow depths (3 to 10 feet) in this area. Evidence for the denitrification included decreases in nitrate concentrations along the flow path to Morgan Creek and enrichment of the ^{15}N isotope. Much less denitrification took place in the Chesterville Branch basin because the top of the reducing sediments are deeper (10 to 20 feet) in this area and a smaller fraction of ground-water flow passed through those sediments.

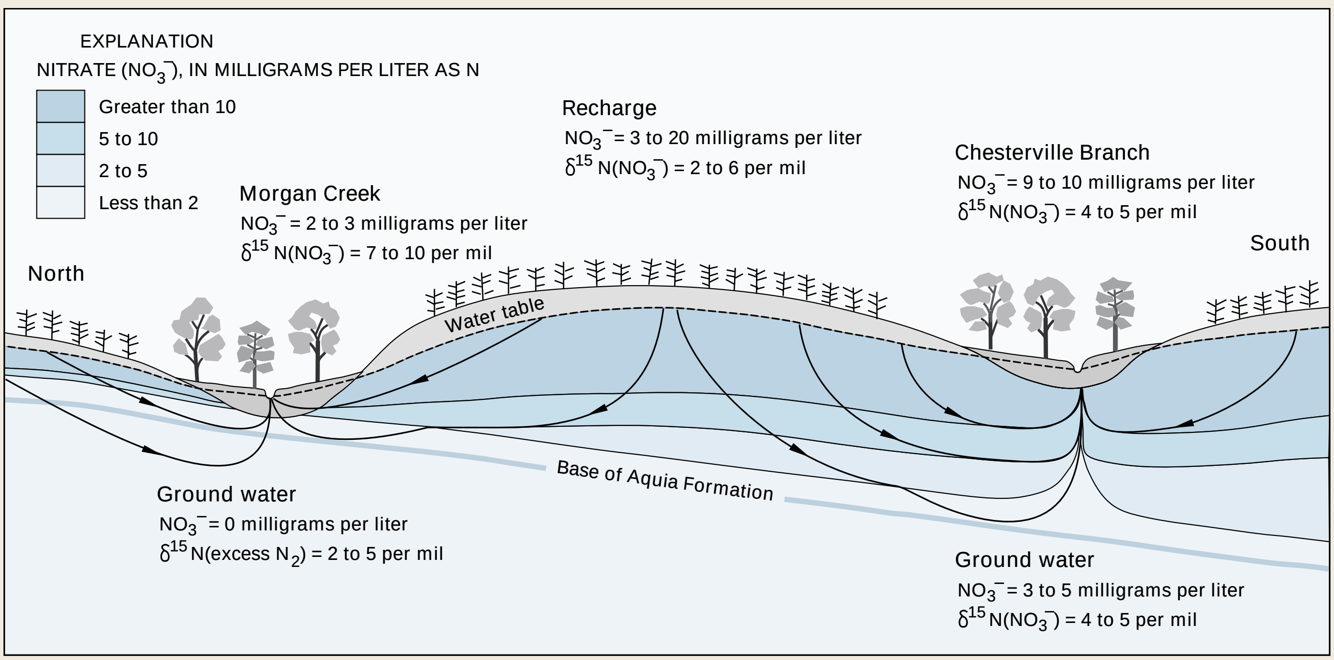


Figure O–2. Denitrification had a greater effect on ground water discharging to Morgan Creek than to Chesterville Branch in Maryland because a larger fraction of the local flow system discharging to Morgan Creek penetrated the reduced calcareous sediments near or below the bottom of the Aquia Formation than the flow system associated with the Chesterville Branch. (Modified from Bolke, J.K., and Denver, J.M., 1995, Combined use of ground-water dating, chemical, and isotopic analyses to resolve the history and fate of nitrate contamination in two agricultural watersheds, Atlantic coastal plain, Maryland: Water Resources Research, v. 31, no. 9, p. 2319–2337.)

P

Effects of Pesticide Application to Agricultural Lands on the Quality of Ground Water and Surface Water

Pesticide contamination of ground water and surface water has become a major environmental issue. Recent studies indicate that pesticides applied to cropland can contaminate the underlying ground water and then move along ground-water flow paths to surface water. In addition, as indicated by the following examples, movement of these pesticides between surface water and ground water can be dynamic in response to factors such as bank storage during periods of high runoff and ground-water withdrawals.

A study of the sources of atrazine, a widely used herbicide detected in the Cedar River and its associated alluvial aquifer in Iowa, indicated that ground water was the major source of atrazine in the river during base-flow conditions. In addition, during periods of high streamflow, surface water containing high concentrations of atrazine moved into the bank sediments and alluvial aquifer, then slowly discharged back to the river as the river level declined. Reversals of flow related to bank storage were documented using data for three sampling periods (Figure P–1). The first sampling (Figure P–1*A*) was before atrazine was applied to cropland, when concentrations in the river and aquifer were relatively low. The second sampling (Figure P–1*B*) was after atrazine was applied to cropland upstream. High streamflow at this time caused the river stage to peak almost 6 feet above its base-flow level, which caused the herbicide to move with the river water into the aquifer. By the third sampling date (Figure P–1*C*), the hydraulic gradient between the river and the alluvial aquifer had reversed again, and atrazine-contaminated water discharged back into the river.

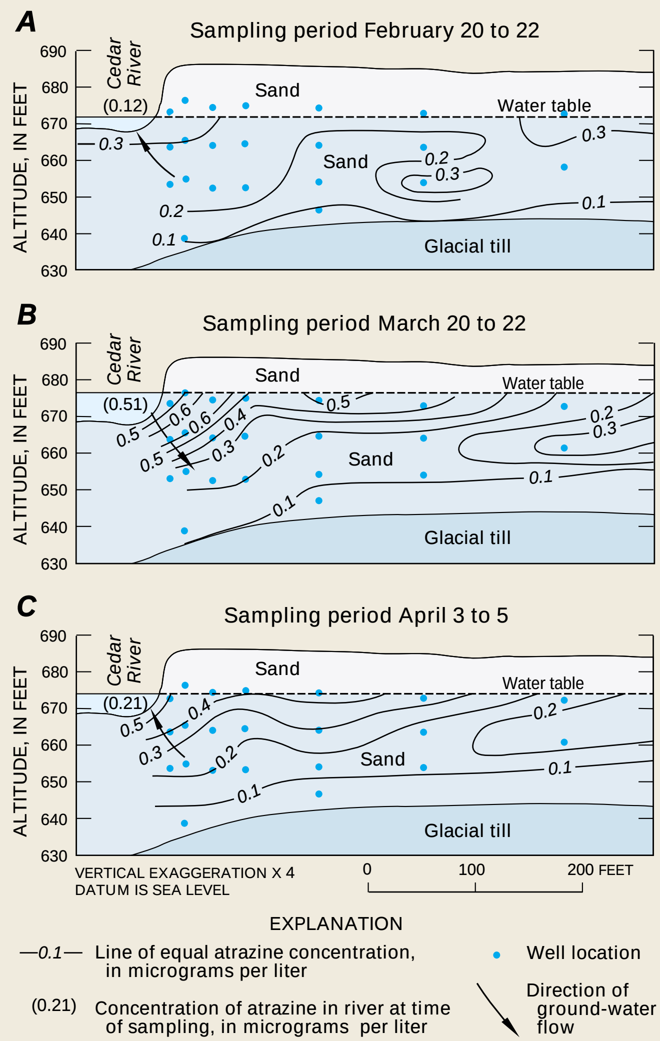
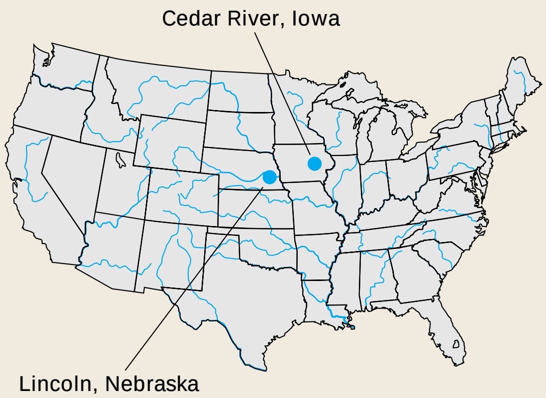


Figure P–1. Concentrations of atrazine increased in the Cedar River in Iowa following applications of the chemical on agricultural areas upstream from a study site. During high streamflow (B), the contaminated river water moved into the alluvial aquifer as bank storage, contaminating ground water. After the river level declined (C), part of the contaminated ground water returned to the river. (Modified from Squillace, P.J., Thurman, E.M., and Furlong, E.T., 1993, Groundwater as a nonpoint source of atrazine and deethylatrazine in a river during base flow conditions: Water Resources Research, v. 29, no. 6, p. 1719–1729.)

In a second study, atrazine was detected in ground water in the alluvial aquifer along the Platte River near Lincoln, Nebraska. Atrazine is not applied in the vicinity of the well field, so it was suspected that ground-water withdrawals at the well field caused contaminated river water to move into the aquifer. To define the source of the atrazine, water samples were collected from monitoring wells located at different distances from the river near the well field. The pattern of concentrations of atrazine in the ground water indicated that peak concentrations of the herbicide showed up sooner in wells close to the river compared to wells farther away (Figure P–2). Peak concentrations of atrazine in ground water were much higher and more distinct during periods of large ground-water withdrawals (July and August) than during periods of much smaller withdrawals (May to early June).



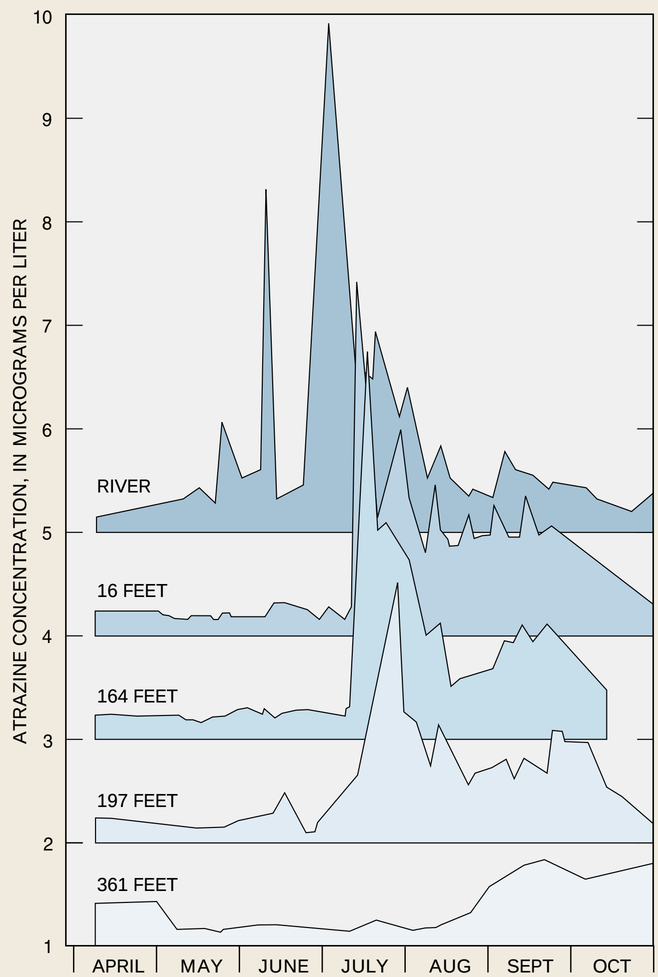


Figure P–2. Pumping of municipal water-supply wells near Lincoln, Nebraska, has induced Platte River water contaminated with atrazine to flow into the aquifer. Distances shown are from river to monitoring well. (Modified from Duncan, D., Pederson, D.T., Shepherd, T.R., and Carr, J.D., 1991, Atrazine used as a tracer of induced recharge: Ground Water Monitoring Review, v. 11, no. 4, p. 144–150.) (Used with permission.)

Urban and Industrial Development

Point sources of contamination to surface-water bodies are an expected side effect of urban development. Examples of point sources include direct discharges from sewage-treatment plants, industrial facilities, and stormwater drains. These facilities and structures commonly add sufficient loads of a variety of contaminants to streams to strongly affect the quality of the stream for long distances downstream. Depending on relative flow magnitudes of the point source and of the stream, discharge from a point source such as a sewage-treatment plant may represent a large percentage of the water in the stream directly downstream from the source. Contaminants in streams can easily affect ground-water quality, especially where streams normally seep to ground water, where ground-water withdrawals induce seepage from the stream, and where floods cause stream water to become bank storage.

Point sources of contamination to ground water can include septic tanks, fluid storage tanks, landfills, and industrial lagoons. If a contaminant is soluble in water and reaches the water table, the contaminant will be transported by the slowly moving ground water. If the source continues to supply the contaminant over a period of time, the distribution of the dissolved contaminant will take a characteristic "plumelike" shape (see Box M). These contaminant plumes commonly discharge into a nearby surface-water body. If the concentration of contaminant is low and the rate of discharge of plume water also is small relative to the volume of the receiving surface-water body, the discharging contaminant plume will have only a small, or perhaps unmeasurable, effect on the quality of the receiving surface-water body. Furthermore, biogeochemical processes may decrease the concentration of the contaminant as it is transported through the shallow ground-water system and the hyporheic zone. On the other hand, if the discharge of the contaminant plume is large or has high concentrations of contaminant, it could significantly affect the quality of the receiving surface-water body.

"Contaminants in streams can easily affect ground-water quality, especially where streams normally seep to ground water, where ground-water withdrawals induce seepage from the stream, and where floods cause stream water to become bank storage"

Drainage of the Land Surface

In landscapes that are relatively flat, have water ponded on the land surface, or have a shallow water table, drainage of land is a common practice preceding agricultural and urban development. Drainage can be accomplished by constructing open ditches or by burying tile drains beneath the land surface. In some glacial terrain underlain by deposits having low permeability, drainage of lakes and wetlands can change the areal distribution of ground-water recharge and discharge, which in turn can result in significant changes in the biota that are present and in the chemical and biological processes that take place in wetlands. Furthermore, these changes can ultimately affect the baseflow to streams, which in turn affects riverine ecosystems. Drainage also alters the water-holding capacity of topographic depressions as well as the surface runoff rates from land having very low slopes. More efficient runoff caused by drainage systems results in decreased recharge to ground water and greater contribution to flooding.

Drainage of the land surface is common in regions having extensive wetlands, such as coastal, riverine, and some glacial-lake landscapes. Construction of artificial drainage systems is extensive in these regions because wetland conditions generally result in deep, rich, organic soils that are much prized for agriculture. In the most extensive artificially drained part of the Nation, the glacial terrain of the upper Midwest, it is estimated that more than 50 percent of the original wetland areas have been destroyed. In Iowa alone, the destruction exceeds 90 percent. Although some wetlands were destroyed by filling, most were destroyed by drainage.

Modifications to River Valleys

CONSTRUCTION OF LEVEES

Levees are built along riverbanks to protect adjacent lands from flooding. These structures commonly are very effective in containing smaller magnitude floods that are likely to occur regularly from year to year. Large floods that occur much less frequently, however, sometimes overtop or breach the levees, resulting in widespread flooding. Flooding of low-lying land is, in a sense, the most visible and extreme example of the interaction of ground water and surface water. During flooding, recharge to ground water is continuous; given sufficient time, the water table may rise to the land surface and completely saturate the shallow aquifer (see Figure 12). Under these conditions, an extended period of drainage from the shallow aquifer takes place after the floodwaters recede. The irony of levees as a flood protection mechanism is that if levees fail during a major flood, the area, depth, and duration of flooding in some areas may be greater than if levees were not present.

CONSTRUCTION OF RESERVOIRS

The primary purpose of reservoirs is to store water for uses such as public water supply, irrigation, flood attentuation, and generation of electric power. Reservoirs also can provide opportunities for recreation and wildlife habitat. Water needs to be stored in reservoirs because streamflow is highly variable, and the times when streamflow is abundant do not necessarily coincide with the times when the water is needed. Streamflow can vary daily in response to individual storms and seasonally in response to variation in weather patterns.

The effects of reservoirs on the interaction of ground water and surface water are greatest near the reservoir and directly downstream from it. Reservoirs can cause a permanent rise in the water table that may extend a considerable distance from the reservoir, because the base level of the stream, to which the ground-water gradients had adjusted, is raised to the higher reservoir levels. Near the dam, reservoirs commonly lose water to shallow ground water, but this water commonly returns to the river as base flow directly downstream from the dam. In addition, reservoirs can cause temporary bank storage at times when reservoir levels are high. In some cases, this temporary storage of surface water in the ground-water system has been found to be a significant factor in reservoir management (see Box Q).

Human-controlled reservoir releases and accumulation of water in storage may cause high flows and low flows to differ considerably in magnitude and timing compared to natural flows. As a result, the environmental conditions in river valleys downstream from a dam may be altered as organisms try to adjust to the modified flow conditions. For example, the movement of water to and from bank storage under controlled conditions would probably be much more regular in timing and magnitude compared to the highly variable natural flow conditions, which probably would lead to less biodiversity in river systems downstream from reservoirs. The few studies that have been made of riverine ecosystems downstream from a reservoir indicate that they are different from the pre-reservoir conditions, but much more needs to be understood about the effects of reservoirs on stream channels and riverine ecosystems downstream from dams.

REMOVAL OF NATURAL VEGETATION

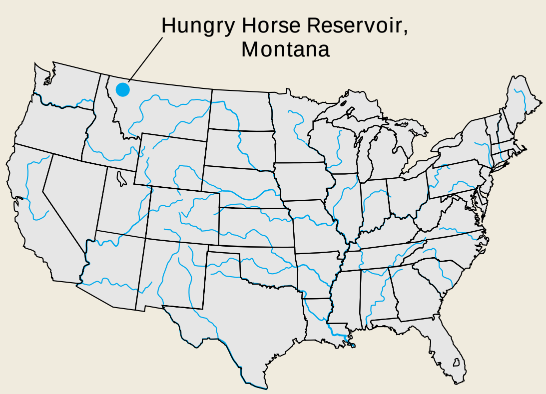
To make land available for agriculture and urban growth, development sometimes involves cutting of forests and removal of riparian vegetation and wetlands. Forests have a significant role in the hydrologic regime of watersheds. Deforestation tends to decrease evapotranspiration, increase storm runoff and soil erosion, and decrease infiltration to ground water and base flow of streams. From the viewpoint of water-resource quality and management, the increase in storm runoff and soil erosion and the decrease in base flow of streams are generally viewed as undesirable.

In the western United States, removal of riparian vegetation has long been thought to result in an increase in streamflow. It commonly is believed that the phreatophytes in alluvial valleys transpire ground water that otherwise would flow to the river and be available for use (see Box R). Some of the important functions of riparian vegetation and riparian wetlands include preservation of aquatic habitat, protection of the land from erosion, flood mitigation, and maintenance of water quality. Destruction of riparian vegetation and wetlands removes the benefits of erosion control and flood mitigation, while altering aquatic habitat and chemical processes that maintain water quality.

Q

Effects of Surface-Water Reservoirs on the Interaction of Ground Water and Surface Water

The increase of water levels in reservoirs causes the surface water to move into bank storage. When water levels in reservoirs are decreased, this bank storage will return to the reservoir. Depending on the size of the reservoir and the magnitude of fluctuation of the water level of the reservoir, the amount of water involved in bank storage can be large. A study of bank storage associated with Hungry Horse Reservoir in Montana, which is part of the Columbia River system, indicated that the amount of water that would return to the reservoir from bank storage after water levels are lowered is large enough that it needs to be considered in the reservoir management plan for the Columbia River system. As a specific example, if the water level of the reservoir is raised 100 feet, held at that level for a year, then lowered 100 feet, the water that would drain back to the reservoir during a year would be equivalent to an additional 3 feet over the reservoir surface. (Information from Simons, W.D., and Rorabaugh, M.I., 1971, Hydrology of Hungry Horse Reservoir, northwestern Montana: U.S. Geological Survey Professional Paper 682.)



R

Effects of the Removal of Flood-Plain Vegetation on the Interaction of Ground Water and Surface Water

In low-lying areas where the water table is close to land surface, such as in flood plains, transpiration directly from ground water can reduce ground-water discharge to surface water and can even cause surface water to recharge ground water (see Figure 7). This process has attracted particular attention in arid areas, where transpiration by phreatophytes on flood plains of western rivers can have a significant effect on streamflows. To assess this effect, a study was done on transpiration by phreatophytes along a reach of the Gila River upstream from San Carlos Reservoir in Arizona. During the first few years of the 10-year study, the natural hydrologic system was monitored using observation wells, streamflow gages, and meteorological instruments. Following this initial monitoring period, the phreatophytes were removed from the flood plain and the effects on streamflow were evaluated. The average effect of vegetation removal over the entire study reach was that the Gila River changed from a continually losing river for most years before clearing to a gaining stream during some months for most years following clearing. Specifically, average monthly values of gain or loss from the stream indicated that before clearing, the river lost water to ground water during all months for most years. After clearing, the river gained ground-water inflow during March through June and during September for most years (Figure R–1).

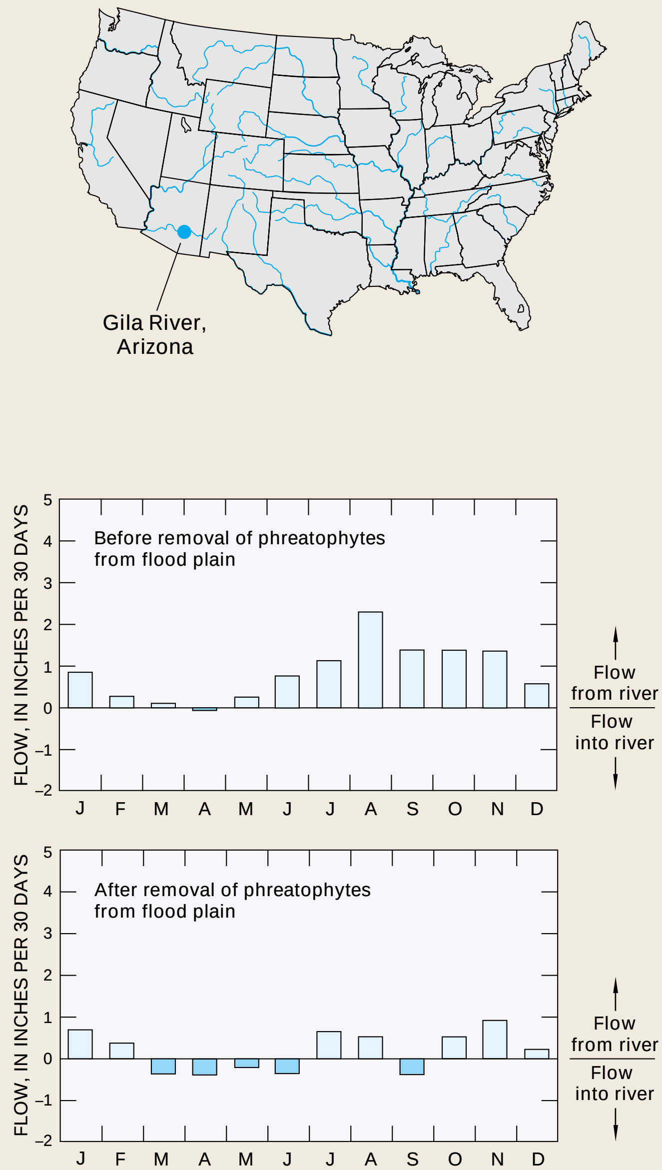


Figure R–1. Removal of phreatophytes from the flood plain along a losing reach of the Gila River in Arizona resulted in the river receiving ground-water inflow during some months of the year. (Modified from Culler, R.C., Hanson, R.L., Myrick, R.M., Turner, R.M., and Kipple, F.P., 1982, Evapotranspiration before and after clearing phreatophytes, Gila River flood plain, Graham County, Arizona: U.S. Geological Professional Paper 655–P.)

Modifications to the Atmosphere

ATMOSPHERIC DEPOSITION

Atmospheric deposition of chemicals, such as sulfate and nitrate, can cause some surface-water bodies to become acidic. Concern about the effects of acidic precipitation on aquatic ecosystems has led to research on the interaction of ground water and surface water, especially in small headwaters catchments. It was clear when the problem was first recognized that surface-water bodies in some environments were highly susceptible to acidic precipitation, whereas in other environments they were not. Research revealed that the interaction of ground water and surface water is important to determining the susceptibility of a surface-water body to acidic precipitation (see Box S). For example, if a surface-water body received a significant inflow of ground water, chemical exchange while the water passed through the subsurface commonly neutralized the acidic water, which can reduce the acidity of the surface water to tolerable levels for aquatic organisms. Conversely, if runoff of acidic precipitation was rapid and involved very little flow through the ground-water system, the surface-water body was highly vulnerable and could become devoid of most aquatic life.

"The interaction of ground water and surface water is important to determining the susceptibility of a surface-water body to acidic precipitation"

GLOBAL WARMING

The concentration of gases, such as carbon dioxide (CO_2) and methane, in the atmosphere has a significant effect on the heat budget of the Earth's surface and the lower atmosphere. The increase in concentration of CO_2 in the atmosphere of about 25 percent since the late 1700s generally is thought to be caused by the increase in burning of fossil fuels. At present, the analysis and prediction of "global warming" and its possible effects on the hydrologic cycle can be described only with great uncertainty. Although the physical behavior of CO_2 and other greenhouse gases is well understood, climate systems are exceedingly complex, and long-term changes in climate are embedded in the natural variability of the present global climate regime.

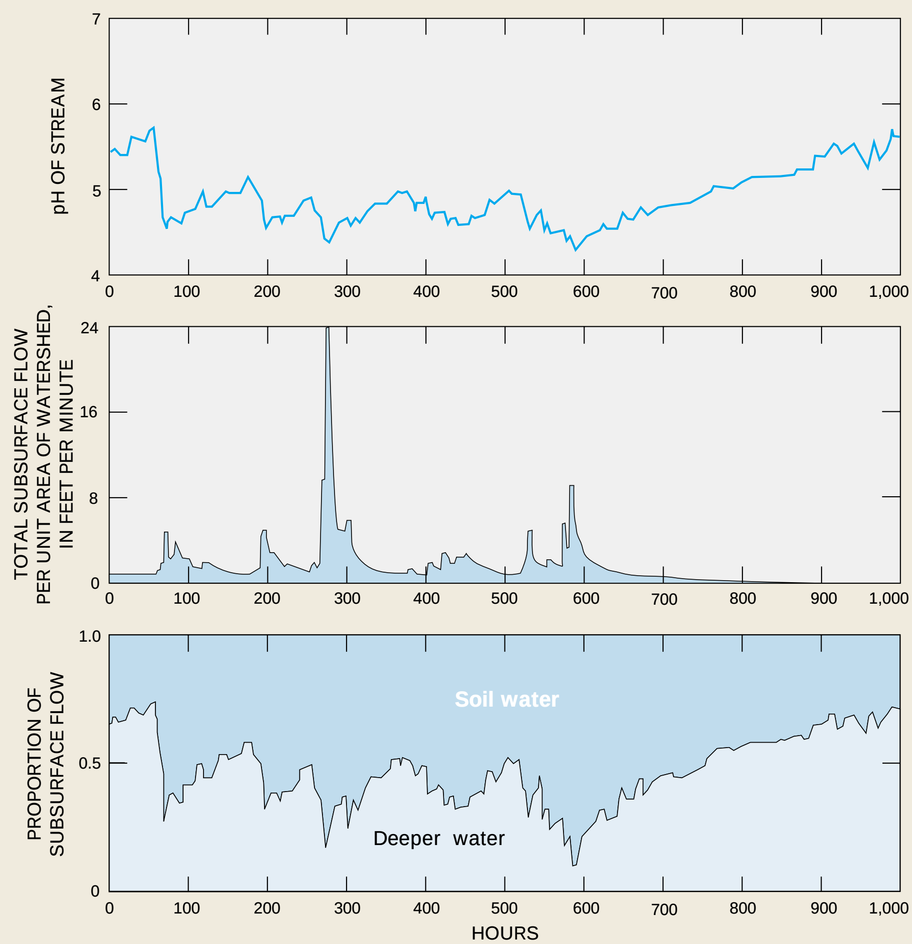
Surficial aquifers, which supply much of the streamflow nationwide and which contribute flow to lakes, wetlands, and estuaries, are the aquifers most sensitive to seasonal and longer term climatic variation. As a result, the interaction of ground water and surface water also will be sensitive to variability of climate or to changes in climate. However, little attention has been directed at determining the effects of climate change on shallow aquifers and their interaction with surface water, or on planning how this combined resource will be managed if climate changes significantly.

S

Effects of Atmospheric Deposition on the Quality of Ground Water and Surface Water

In areas where soils have little capacity to buffer acids in water, acidic precipitation can be a problem because the infiltrating acidic water can increase the solubility of metals, which results in the flushing of high concentrations of dissolved metals into surface water. Increased concentrations of naturally occurring metals such as aluminum may be toxic to aquatic organisms. Studies of watersheds have indicated that the length of subsurface flow paths has an effect on the degree to which acidic water is buffered by flow through the subsurface. For example, studies of watersheds in England have indicated that acidity was higher in streams during storms when more of the subsurface flow moved through the soil rather than through the deeper flow paths (Figure S–1). Moreover, in a study of the effects of acid precipitation on lakes in the Adirondack Mountains of New York, the length of time that water was in contact with deep subsurface materials was the most important factor affecting acidity because contact time determined the amount of buffering that could take place (Figure S–2).

Figure S–1. Acidity is higher (pH is lower) in streams when most of the flow is contributed by shallow soil water because the water has had less time to be neutralized by contact with minerals compared to water that has traversed deeper flow paths. (Modified from Robson, A., Beven, K.J., and Neal, C., 1992, Towards identifying sources of subsurface flow—A comparison of components identified by a physically based runoff model and those determined by chemical mixing techniques: Hydrological Processes, v. 6, p. 199–214.) (Reprinted with permission from John Wiley & Sons Limited.)



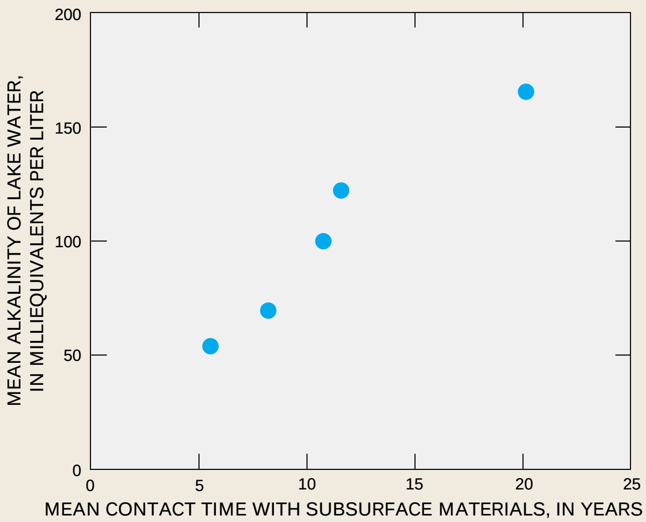


Figure S–2. The longer water is in contact with deep subsurface materials in a watershed, the higher the alkalinity in lakes receiving that water. (Modified from Wolock, D.M., Hornberger, G.M., Beven, K.J., and Campbell, W.G., 1989, The relationship of catchment topography and soil hydraulic characteristics to lake alkalinity in the northeastern United States: Water Resources Research, v. 25, p. 829–837.)

CHALLENGES AND OPPORTUNITIES

The interaction of ground water and surface water involves many physical, chemical, and biological processes that take place in a variety of physiographic and climatic settings. For many decades, studies of the interaction of ground water and surface water were directed primarily at large alluvial stream and aquifer systems. Interest in the relation of ground water to surface water has increased in recent years as a result of widespread concerns related to water supply; contamination of ground water, lakes, and streams by toxic substances (commonly where not expected); acidification of surface waters caused by atmospheric deposition of sulfate and nitrate; eutrophication of lakes; loss of wetlands due to development; and other changes in aquatic environments. As a result, studies of the interaction of ground water and surface water have expanded to include many other settings, including headwater streams, lakes, wetlands, and coastal areas.

Issues related to water management and water policy were presented at the beginning of this report. The following sections address the need for greater understanding of the interaction of ground water and surface water with respect to the three issues of water supply, water quality, and characteristics of aquatic environments.

Water Supply

Water commonly is not present at the locations and times where and when it is most needed. As a result, engineering works of all sizes have been constructed to distribute water from places of abundance to places of need. Regardless of the scale of the water-supply system, development of either ground water or surface water can eventually affect the other. For example, whether the source of irrigation water is ground water or surface water, return flows from irrigated fields will eventually reach surface water either through ditches or through ground-water discharge. Building dams to store surface water or diverting water from a stream changes the hydraulic connection and the hydraulic gradient between that body of surface water and the adjacent ground water, which in turn results in gains or losses of ground water. In some landscapes, development of ground water at even a great distance from surface water can reduce the amount of ground-water inflow to surface water or cause surface water to recharge ground water.

The hydrologic system is complex, from the climate system that drives it, to the earth materials that the water flows across and through, to the modifications of the system by human activities. Much research and engineering has been devoted to the development of water resources for water supply. However, most past work has concentrated on either surface water or ground water without much concern about their interrelations. The need to understand better how development of one water resource affects the other is universal and will surely increase as development intensifies.

Water Quality

For nearly every type of water use, whether municipal, industrial, or agricultural, water has increased concentrations of dissolved constituents or increased temperature following its use. Therefore, the water quality of the water bodies that receive the discharge or return flow are affected by that use. In addition, as the water moves downstream, additional water use can further degrade the water quality. If irrigation return flow, or discharge from a municipal or industrial plant, moves downstream and is drawn back into an aquifer because of ground-water withdrawals, the ground-water system also will be affected by the quality of that surface water.

Application of irrigation water to cropland can result in the return flow having poorer quality because evapotranspiration by plants removes some water but not the dissolved salts. As a result, the dissolved salts can precipitate as solids, increasing the salinity of the soils. Additional application of water dissolves these salts and moves them farther downgradient in the hydrologic system. In addition, application of fertilizers and pesticides to cropland can result in poor-quality return flows to both ground water and surface water. The transport and fate of contaminants caused by agricultural practices and municipal and industrial discharges are a widespread concern that can be addressed most effectively if ground water and surface water are managed as a single resource.

Water scientists and water managers need to design data-collection programs that examine the effects of biogeochemical processes on water quality at the interface between surface water and near-surface sediments. These processes can have a profound effect on the chemistry of ground water recharging surface water and on the chemistry of surface water recharging ground water. Repeated exchange of water between surface water and near-surface sediments can further enhance the importance of these processes. Research on the interface between ground water and surface water has increased in recent years, but only a few stream environments have been studied, and the transfer value of the research results is limited and uncertain.

The tendency for chemical contaminants to move between ground water and surface water is a key consideration in managing water resources. With an increasing emphasis on watersheds as a focus for managing water quality, coordination between watershed-management and ground-water-protection programs will be essential to protect the quality of drinking water. Furthermore, ground-water and surface-water interactions have a major role in affecting chemical and biological processes in lakes, wetlands, and streams, which in turn affect water quality throughout the hydrologic system. Improved scientific understanding of the interconnections between hydrological and biogeochemical processes will be needed to remediate contaminated sites, to evaluate applications for waste-discharge permits, and to protect or restore biological resources.

Characteristics of Aquatic Environments

The interface between ground water and surface water is an areally restricted, but particularly sensitive and critical niche in the total environment. At this interface, ground water that has been affected by environmental conditions on the terrestrial landscape interacts with surface water that has been affected by environmental conditions upstream. Furthermore, the chemical reactions that take place where chemically distinct surface water meets chemically distinct ground water in the hyporheic zone may result in a biogeochemical environment that in some cases could be used as an indicator of changes in either terrestrial or aquatic ecosystems. The ability to understand this interface is challenging because it requires the focusing of many different scientific and technical disciplines at the same, areally restricted locality. The benefit of this approach to studying the interface of ground water and surface water could be the identification of useful biological or chemical indicators of adverse or positive changes in larger terrestrial and aquatic ecosystems.

Wetlands are a type of aquatic environment present in most landscapes; yet, in many areas, their perceived value is controversial. The principal characteristics and functions of wetlands are determined by the water and chemical balances that maintain them. These factors in large part determine the value of a wetland for flood control, nutrient retention, and wildlife habitat. As a result, they are especially sensitive to changing hydrological conditions. When the hydrological and chemical balances of a wetland change, the wetland can take on a completely different function, or it may be destroyed. Generally, the most devastating impacts on wetlands result from changes in land use. Wetlands commonly are drained to make land available for agricultural use or filled to make land available for urban and industrial development. Without understanding how wetlands interact with ground water, many plans to use land formerly occupied by wetlands fail. For example, it is operationally straightforward to fill in or drain a wetland, but the ground-water flow system that maintains many wetlands may continue to discharge at that location. Many structures and roads built on former wetlands and many wetland restoration or construction programs fail for this reason. Saline soils in many parts of the central prairies also result from evaporation of ground water that continues to discharge to the land surface after the wetlands were drained.

Riparian zones also are particularly sensitive to changes in the availability and quality of ground water and surface water because these ecosystems commonly are dependent on both sources of water. If either water source changes, riparian zones may be altered, changing their ability to provide aquatic habitat, mitigate floods and erosion, stabilize shorelines, and process chemicals, including contaminants. Effective management of water resources requires an understanding of the role of riparian zones and their dependence on the interaction of ground water and surface water.

ACKNOWLEDGMENTS

Technical review of this Circular was provided by S.P. Garabedian, J.W. LaBaugh, E.M. Thurman, and K.L. Wahl of the U.S. Geological Survey, and James Goeke of the Nebraska Conservation and Survey Division, University of Nebraska. J.V. Flager provided technical and editorial reviews of the manuscript at several stages during its preparation, and M.A. Kidd edited the final manuscript. Design and production of the Circular were led by R.J. Olmstead. Conceptual landscapes were provided by J.M. Evans, and manuscript preparation was provided by J.K. Monson.

DEPARTMENT OF
ECOLOGY
State of Washington

Economic Impact Analysis

National Pollutant Discharge Elimination System (NPDES) Wastewater Discharge General Permit

Industrial Stormwater General Permit

May 2009
Publication no. 09-10-041

Publication and Contact Information

This report is available on the Department of Ecology's website at
www.ecy.wa.gov/biblio/0910041.html

For more information contact:

Water Quality Program
P.O. Box 47600
Olympia, WA 98504-7600

Phone: 360-407-6400

Washington State Department of Ecology - www.ecy.wa.gov

○ Headquarters, Olympia	360-407-6000
○ Northwest Regional Office, Bellevue	425-649-7000
○ Southwest Regional Office, Olympia	360-407-6300
○ Central Regional Office, Yakima	509-575-2490
○ Eastern Regional Office, Spokane	509-329-3400

To ask about the availability of this document in a format for the visually impaired, call the Water Quality Program at 360-407-6400. Persons with hearing loss can call 711 for Washington Relay Service. Persons with a speech disability can call 877-833-6341.

Economic Impact Analysis

National Pollutant Discharge Elimination System (NPDES) Wastewater Discharge General Permit

---

Industrial Stormwater General Permit

Prepared by

Sarah Wilson

Water Quality Program
Washington State Department of Ecology
Olympia, Washington

This page is purposely left blank

Table of Contents

Executive Summary

The Industrial Stormwater General Permit is a statewide permit that provides coverage for discharges of stormwater from industrial facilities. The permit specifically regulates discharges of stormwater to surface water bodies.

WAC 173-226-120 requires an economic analysis of any proposed water-quality general permit to serve the following purposes. The analysis must provide:

- A brief description of the compliance requirements of the general permit.
- The estimated costs for complying with the permit, based upon existing data for facilities intended to be covered under the general permit.
- A comparison, to the greatest extent possible, of the cost of compliance for small businesses with the cost of compliance for the largest ten percent of the facilities intended to be covered under the general permit.
- A summary of how the permit provides mitigation to reduce the effect on small businesses (if a disproportionate impact is expected), without compromising the mandated intent of the permit.

A small business is defined as any business entity, including a sole proprietorship, corporation, partnership, or other legal entity, that is owned and operated independently from all other businesses, and that has 50 or fewer employees.

Costs to comply with the new permit

Depending on the industry sector of the facility, Ecology determined annualized compliance costs might be *$500 - $1,300 for small businesses and $1,000 - $2,500 for large businesses*.

Ecology used cost-to-sales ratio as the measure of proportionate impact. It is an approximate estimate of the percentage rise in costs caused by the permit. This is likely to be how the permit holder looks at compliance costs.

To calculate the ratio, Ecology divided annualized compliance costs by midrange annual sales. The cost-to-sales ratios fall as sales rise, so larger businesses–which employ more people, but have disproportionately higher sales–incur a lower cost per $100 of sales. Ecology concluded, based on this result, that *the general permit has a disproportionate impact on small businesses.*

In all the typical cases analyzed, costs to comply are no higher than 0.075 percent of sales, which is only 7.5 cents per $100 of sales. The numbers presented in this analysis show the typical large business is 7 to 30 times larger than the typical small business. At the same time, while a large business will possibly require more sampling than a small one, it does not need 10 times as much. Therefore, it is difficult to avoid disproportionate costs for smaller businesses, as small businesses will always be disproportionately impacted, relative to large businesses.

Ecology can offer very little mitigation without violating requirements of the state or federal water pollution control laws. However, the new permit does reduce some costs; these pertain mostly to all facilities, not only small businesses.

Changes to the permit

The new permit removes the requirements for:

- New operations to submit Stormwater Pollution Prevention Plans (SWPPPs) to Ecology during the permit application process.
- Facilities to submit Level 1, 2, or 3 Source Control Reports to Ecology.
- Facilities to perform extensive and specific sampling criteria.
- Facilities to conduct total copper and total lead sampling/analysis if total zinc levels exceeded the limit for two consecutive quarters.
- Facilities to submit a Notice of Termination when they receive a Conditional No Exposure exemption.
- Facilities to conduct oil and grease sampling and lab analysis and replaces it with the requirement for a visual assessment of "oil sheen."
- Existing facilities (in operation prior to the effective date of the permit) to complete public notice requirements during the permit application process.

The new permit gives:

- Facilities the option to request a modification of coverage to:
    - Get an extension to complete required corrective actions.
    - Receive an exemption from installing additional structural source control and/or treatment BMPs.
- Small businesses three years to ensure the personnel who conduct site inspections are trained and certified– large businesses have two years to comply with this requirement.
- Facilities the ability to incorporate other plans into SWPPPs.
- An exemption for sampling and analysis with the demonstration of "consistent attainment" of benchmarks.

Chapter 1: Compliance Requirements for the Industrial Stormwater General Permit

Permit overview

The Industrial Stormwater General Permit regulates stormwater discharges from industrial facilities to surface water bodies.

Ecology requires industrial facilities that conduct activities under specific Standard Industrial Classification (SIC) codes to apply for a permit if they discharge stormwater from their industrial areas to storm drains or directly to surface waters.

Ecology does not require facilities to get a permit if they retain all the stormwater on site (e.g., infiltrate into the ground, or discharge to sanitary sewer). If the facility has no potential to expose stormwater to pollutants, that facility may apply for a Conditional No Exposure Certificate so they are exempt from the general permit.

This statewide permit currently provides coverage for approximately 1,200 industrial facilities that discharge stormwater to waters of the state.

Stormwater Pollution Prevention Plan (SWPPP)

All permit holders and applicants for coverage under this permit are required to develop a SWPPP for the permitted facility. The SWPPP must contain:

- A site map.
- A detailed assessment of the facility.
- A detailed description of the BMPs necessary to:
    - Provide all known, available and reasonable methods of prevention, control and treatment (AKART).
    - Comply with state water quality standards and applicable federal technology-based treatment requirements under 40 CFR 125.3.
- A sampling plan.

The SWPPP must also have proper selection and use of stormwater management manuals (SWMM).

Sampling and testing

The general permit requires all facilities that discharge to non-303(d) listed water bodies to sample the stormwater discharge from designated locations at least once per quarter (4 times a year) as outlined in the SWPPP. The designated sampling locations must capture stormwater with the greatest exposure to significant sources of pollution. Each sample must be visually monitored for oil sheen and tested using the following 3 parameters:

1. Turbidity
2. pH
3. Zinc, Total

Facilities must also ensure the analytical methods used to meet the sampling requirements conform to the latest versions of the:

- *Guidelines Establishing Test Procedures for the Analysis of Pollutants* contained in 40 CFR Part 136 or
- *Standard Methods for the Examination of Water and Wastewater* (APHA).

For each stormwater sample taken, facilities must record the following in the site log:

- Sample date, time, and location
- Method of sampling and method of sample preservation
- Name of person who performed the sampling

Facilities must also keep laboratory reports in the site log. All laboratory reports must include the following information:

- Date of analysis
- Parameter name
- CAS number
- Analytical method(s)
- Name of person who performed the analysis
- Method detection limit (MDL)
- Laboratory practical quantitation level (PQL) achieved by the laboratory
- Reporting units
- Sample result
- Quality assurance/quality control data

Additional testing requirements

A variety of industrial groups are required to test for other pollutants that are likely to be present in their discharge. The costs for a representative selection of industrial groups are analyzed in Chapter 3. Table 1 lists the additional required tests for the selected industry. Ecology is also adding a new set of requirements for stormwater from Hazardous Waste Treatment, Storage and Disposal Facilities and Dangerous Waste Recyclers subject to Resource Conservation and Recovery Act (RCRA) Subtitle D.

Table 1: Industry groups required to conduct additional testing

Industrial Group	Types of Pollutant
Timber Product Industry and Paper Allied Products	• Biological Oxygen Demand (BOD5) • Chemical Oxygen Demand (COD)* • Total Suspended Solids (TSS)*
Air Transportation	• Ammonia* • BOD5* • Nitrate/Nitrate, as Nitrogen
Chemical and Allied Products, Food and Kindred Products	• BOD5* • Nitrate/Nitrate, as Nitrogen*

Industrial Group	Types of Pollutant
	• Phosphorous, Total
Primary Metals, Metals Mining, Automobile Salvage and Scrap Recycling, Metals Fabricating	• Lead, Total (applies to 10xx, 5015, 5093, in MSGP) • Copper Total (applies to SIC 33xx, 10xx, 5093, in MSGP) • Total Petroleum Hydrocarbons (TPH)
Hazardous Waste Treatment Storage, and Disposal Facilities and Dangerous Waste Recyclers	• COD* • Ammonia, Total* • TSS • Arsenic, Total* • Cadmium, Total* • Cyanide, Total* • Lead, Total * • Magnesium, Total* • Mercury, Total* • Selenium, Total* • Silver, Total* • Total Petroleum Hydrocarbons (TPH)
* Theses pollutants are also required to be analyzed in EPAs Multi-Sector General Permit for Stormwater Discharges associated with Industrial Activities and therefore they are not analyzed. If the pollutant is not required by all sectors in the MSGP then, to be conservative, it is analyzed here.	

Visual inspections

Facilities must now conduct visual inspections of the site each month and document these inspections in the SWPPP. Each inspection shall consist of:

- Observations made at sampling locations and areas where stormwater is discharged.
- Observations for the presence of floating materials, visible sheen, discoloration, etc., in the stormwater discharge.
- Observation for the presence of illicit discharges.
- Verification that the descriptions of potential pollutant source required under this permit are accurate.
- Verification that the site map in the SWPPP reflects current conditions.
- Assessment of all BMPs that have been implemented.

Corrective actions

Facilities that exceed benchmarks are required to follow the four level corrective action process outlined in the permit. The level of corrective action depends on the number of benchmarks exceeded. Please refer to Special Conditions-8 of the permit for details.

Reporting and recordkeeping

The general permit sets reporting and recordkeeping requirements for all facilities.

Reporting

Facilities must use Discharge Monitoring Report (DMR) forms to report the sampling data they collect each reporting period. The reporting periods and subsequent due dates for receipt of DMRs by Ecology are as follows:

Table 2: Reporting Dates and DMR Due Dates

Reporting Dates and DMR Due Dates		
Reporting Period	**Months**	**DMR Due Date**
1st	January - March	May 15th
2nd	April – June	August 15th
3rd	July – September	November 15th
4th	October - December	February 15th

Records retention

Facilities must retain the following records on site for a minimum of 5 years:

- A copy of the permit.
- A copy of the permit coverage letter.
- Records of all sampling information.
- Inspection reports.
- Any other documentation of compliance with permit requirements.
- All equipment calibration records.
- All BMP maintenance records.
- All original recordings for continuous sampling instrumentation.
- Copies of all laboratory reports.
- Copies of all reports required by this permit.
- Records of all data used to complete the application for the permit.
- Any records that can substantiate compliance with the permit.

Chapter 2: Overview of Analysis

This Economic Impact Analysis (EIA) estimates the costs of complying with the general permit. It also compares the costs of complying with the permit for small businesses, to the costs of compliance for large businesses, in order to determine whether the permit disproportionately impacts small businesses.

Definition of small and large businesses

For the purpose of this study, a small business is an independent entity with 50 or fewer employees organized for the purpose of making a profit. Enterprises owned by larger corporations are excluded, as are not-for-profit and government enterprises. There are both small and large businesses that must comply with this permit.

The following SIC (Standard Industry Codes) Code Groups are required to obtain permit coverage. This activity does not have to be the primary activity for a facility; it only has be part of a facility's activities.

Table 3: Impacted Industries SIC Codes

Impacted Industries SIC Codes					
10xx	12xx	13xx	14xx	20xx	21xx
22xx	23xx	24xx	25xx	26xx	27xx
28xx	29xx	30xx	31xx	32xx	33xx
34xx	35xx	36xx	37xx	38xx	39xx
4221	4222	4225	5015	5093	5191
4953	4952	2869	42xx	44xx	45xx
5171	40xx	41xx	43xx		

Compliance costs included in the EIA

According to WAC 173-226-120, the EIA must estimate the costs of the following:

- Minimum treatment technology
- Monitoring
- Reporting
- Recordkeeping
- Plan submittal
- Equipment
- Supplies
- Labor
- Administrative costs

The following table is a summary of the permit requirements, and the last column indicates whether Ecology is required to consider the costs associated with each section for the economic analysis.

Table 4: Compliance costs included in the EIA

Requirement	Condition Number	Basis of Requirement	Required to be in EIA
Submittal of application for coverage	S2.A	Federal	No
Development of SWPPP	S3	Federal	No
General sampling requirements	S4	Federal (once/year) State (quarterly)	Yes, 3 extra samples
Specific sampling parameters			
Core parameters	S5.A	State	Yes
Industry-specific parameters	S5.B	Federal and State[1]	Yes
Industries with effluent limits	S5.C	Federal	No
Sampling discharges to impaired waters			
Discharges to 303(d)-listed waters	S6	State[2]	No
Discharges to waters with TMDLs	S6	State[2]	No
Inspections	S7	Federal (quarterly) State (monthly)	Yes, 8 extra inspections
Corrective Actions	S8	State[3]	No
Reporting and Recordkeeping			
Reporting DMRs	S9.A	Federal	No
Records Retention	S9.B	Federal (3 years) State (all 5 years)	Yes, 2 extra years
Non-Compliance	S9.D	Federal	No

Compliance costs excluded from the EIA

The cost of complying with permit conditions required by the following laws and rules are not included in the EIA's analysis of compliance costs:

1. State Groundwater Quality Standards (WAC 173-200)
2. State Surface Water Quality Standards (WAC 173-201)
3. State Sediment Management Standards (WAC 173-204)
4. Wastewater Discharge Permit Fees (WAC 173-224)

[1] Some of the specific sampling requirements are in the Federal Multi-Sector General Permit (MSGP) and therefore they will not be analyzed. However, any sampling requirements not in the MSGP will be analyzed.

[2] MSGP largely defers to the appropriate state authority. Sampling requirements in Ecology's permit are primarily a state requirement. However, since the benchmarks are based on the acute water quality criterion in WAC Chapter 173-201A, the economic analysis is not allowed to consider these sampling costs.

[3] MSGP does not require eventual compliance with all benchmarks and therefore the corrective action and adaptive management set in this permit are primarily a state requirement. However, these benchmarks and the adaptive management conditions are necessary to comply with WAC 173-201 (Water Quality Standards) and are therefore exempt from the economic analysis.

5. Federal law and regulations, in particular the Clean Water Act and federal NPDES regulations.

The justification for excluding compliance costs related to these laws and rules is that permit holders cannot be exempt from these laws through the permit process and, therefore, any cost impacts of these laws and regulations cannot be mitigated. Permit holders must comply with existing regulation independent of permit requirements.

Facilities covered under the existing permit are already expected to be in compliance with the majority of the new general permit's requirements. They have already incurred some or all of the costs of complying with the permit. However, even though a certain compliance cost has been incurred in the past, it is still a cost of compliance.

Analysis of facilities intended to be covered under the general permit

The permit involves six different levels of monitoring for different industry sectors. One of these sectors, Hazardous Material Recyclers and TSDs, has at least nine companies in the state and a very different list of tests for monitoring so we analyzed them separately.[4]

The other sectors are large with a wide variety of company types, so we analyzed a representative sector in each of these five groups. The criteria for "representative" are below:

1. The analysis required the use of data sources built on the old Standard Industrial Classification (SIC) system together with sources, which use the new North American Industry Classification System (NAICS). Therefore, there must be a reasonable "mapping" between a given SIC sector and some corresponding NAICS sector(s).
2. The sector must have a mix of large and small businesses in Washington.
3. Within the previous two criteria, the sector should be as highly represented as possible among holders of the stormwater general permit (permit-holders are still classified by SIC).

Data used in analysis

The first step in the calculation is to estimate a range of sales for small and large firms within the given sector. For each sector chosen, sales and employment are taken from the Economic Census 2002 (which uses NAICS). These data are presented in Table 5 below.

These figures yielded an average level of sales per employee in the sector within Washington. Firm size data are then gathered from the County Businesses Patterns (CBP) 2004. The CBP data give numbers of firm in certain size ranges defined by the number of employees (for instance, how many firms in an industry have 1 to 4 employees, or 5 to 9 employees, etc.). These data are also presented in Table 5.

[4] The economic data for this subset was drawn from a larger group.

By taking the mid-points of these employee ranges, we can derive a range of typical sizes for both small and the 10 percent of firms that are the largest in the industry. These data are also presented in Table 5.

Multiplying these firm sizes by the sales-per-employee numbers derived in the first step of the calculation described above, we get estimates of average sales by small and large firms in the sector. This data is presented in Table 6.

Table 5: Sales and Employment Data

Sales and Employment Data						
Descriptions	1987 SIC	2002 NAICS	2002 Economic Census		County Business Patterns	
			Sales	Paid Employees	Average Employees	
					Small	Large
Refuse Systems	4953	5622, 562920	$929,778,000	5,837	15.6	221.4
Sawmills and Planning Mills, General	2421	321113, 3219	$3,165,378,000	14,421	12.7	203.6
Airports, Flying Fields & Airport Terminal Services	4581	4881	$379,504,000	4,629	15.3	513.9
Prepared Fresh or Frozen Fish and Seafood	2092	311712	$1,138,017,000	6,580	20.2	300.0
Scrap and Waste Materials, Metals	5093	423930	$420,058,000	1,508	9.0	100.0
Hazardous Waste: Treatment Storage Disposal	4953	562211, 562112	$852,193,000	5,184	17.8	124.5

Table 6: Calculations

Calculations					
Descriptions	1987 SIC	2002 NAICS	Sales per Employee	Estimated Sales	
				Small	Large
Refuse Systems	4953	5622, 562920	$159,290	$2,480,800	$35,271,443
Sawmills and Planning Mills, General	2421	321113, 3219	$219,498	$2,785,934	$44,683,484
Airports, Flying Fields & Airport Terminal Services	4581	4881	$81,984	$1,250,256	$42,683,484
Prepared Fresh or Frozen Fish and Seafood	2092	311712	$172,951	$3,489,539	$51,885,274
Scrap and Waste Materials, Metals	5093	423930	$278,553	$2,518,394	$27,855,305
Hazardous Waste: Treatment Storage Disposal	4953	562211, 562112	$164,389	$2,927,390	$20,466,441

Chapter 3: Estimated Costs for Complying with the Permit

Compliance costs are dependent on size of the facility. In this chapter, Ecology estimated ranges of costs for most requirements–a low cost and a high cost. The low cost estimate is for small facilities and the high cost estimate is for large facilities. Some requirements have the same cost for small and large businesses.

Most of the major assumptions used in making the compliance cost estimates are presented in this chapter. In general, we assume that large facilities will have twice as many samples and requirements will take twice as long to complete. In addition, assumptions used in making estimates of capital costs are included. Capital costs are annualized to compare them to services facilities provide annually.

It is necessary to annualize costs because some costs are annual (incurred every year), while other costs are capital costs (incurred once). For example, equipment for pH testing is a one-time capital cost, while monitoring is an annual cost that must be incurred every year.

Estimated costs for sampling and monitoring

All facilities must sample and monitor their discharges four times a year. Water Quality Program staff provided estimates for the employee time needed to carry out each of the major tasks required by the permit, divided into time of professional or supervisory personnel and time of other employees.

The draft economic analysis of 2005 used labor costs of $67.37 per hour for professional or supervisory personnel and $21.56 per hour for employees. These costs included salaries, benefits and overhead. For the present study, the costs are brought up to date by applying a 4.7 percent inflationary factor 2006-2009.[5]

The calculations in Table 7 are based on $70.52 for professional or supervisory personnel and $22.57 for employees. For activities associated with monitoring (such as sample collection, record keeping, reporting), large firms are assumed to require twice as much labor as small firms, to reflect greater sampling activity.

---

[5] U.S. Department of Commerce: Bureau of Economic Analysis, Gross National Product: Implicit Price Deflator http://research.stlouisfed.org/fred2/data/GNPDEF.txt

Table 7: Labor Costs for Sampling and Monitoring Small and Large Businesses

Labor Costs for Sampling and Monitoring Small and Large Businesses				
	Small Businesses		Large Businesses	
	Prof/Sup	Staff	Prof/Sup	Staff
Sampling	1 – 2 hr	6 – 12 hr	2 – 4 hr	12 – 24 hr
Training	0 – 2 hr	0 hr	0 – 4 hr	0 hr
Recordkeeping	0 hr	2 – 4 hr	0 hr	4 – 8 hr
Total Time	1 – 4 hr	8 – 16 hr	2 – 8 hr	16 – 32 hr
Cost	$71 - $282	$181 - $361	$141- $564	$361 - $722
Total Annual Labor Cost	**$251 - $643**		**$502 - $1,286**	

Estimated costs for lab analysis

The permit also requires samples to be sent to a laboratory for analysis. In 2007, Ecology surveyed the three primary labs used by TSDs regarding their fees for various water quality parameters. These values have been indexed to 2009 dollar values. This provided average fee levels for each of the monitoring parameters required by the stormwater general permit.

It is assumed that small firms will have 1 sample analyzed for each parameter, while large firms will have 2 samples analyzed for each parameter, to reflect the probability that sampling in more than one location would be necessary to capture the impact of a large installation. These lab fees only include the cost for analyzing parameters that are not required in the Federal Multi-Sector General Permit.

Table 8: Annual Laboratory Fees

Annual Laboratory Fees				
Sector	**SIC**	**Testing Group**	**Small**	**Large**
Refuse Systems	4953	Basic	$135	$269
Sawmills and Planning Mills, General	2421	Timber Products etc	$162	$323
Airports, Flying Fields, and Airport Terminal Services	4581	Air Transportation	$99	$199
Prepared Fresh or Frozen Fish and Seafood	2029	Chemicals and food	$162	$323
Scrap and Waste Material	5093	Primary metals etc	$448	$895
Hazardous Waste: Treatment, Storage & Disposal	4953	TSDs	$394	$787

In 1998 Ecology's Lab Accreditation Program surveyed environmental laboratories to get information on equipment requirements for pH testing. For a sample to be valid, pH testing needs to be done immediately after a sample is drawn. Ecology annualized values for long-term purchase based on a 3 percent real rate of interest and a 5-year period of use.

A suitable pH meter and probe was assumed to cost $225, with annual replacement parts costs of $56.[6] For the low cost estimate, facilities were assumed to already own the equipment, leaving only the annual purchase of replacement parts. Large firms were assumed to have twice the replacements parts costs, to reflect increased sampling. There are no lab fees for pH analysis because pH testing is done on site.

[6] Indexed from 1995 values. Some facilities are not subject to pH limits and can therefore use litmus paper rather than having to use a meter. This is a considerable savings, so the inclusion of the meter cost in the analysis is a conservative assumption, tending to make the estimated compliance costs higher than the actual compliance costs.

Table 9: Equipment Costs for pH Testing

Equipment Costs for pH Testing		
	Small	**Large**
Initial Cost, Annualized	$0 - $49	$0 - $49
Annual Replacement Cost	$56 - $56	$113 - $113
Total Annual Cost	$56 - $105	$113 - $162

Estimated cost for visual inspections

Facilities are required to visually inspect their site each month and document the inspection in the SWPPP. The Federal MSGP requires only quarterly inspections, so Ecology estimated the cost for the additional 8 inspections. Ecology assumes visual inspection will take a small businesses .5 hours and large businesses 1 hour. Ecology assumes a staff wage of $22.57 per hour.

Table 10: Inspection Costs for Small and Large Businesses

Inspection Costs for Small and Large Businesses								
	Small Businesses				**Large Businesses**			
Method	**Hours**	**Frequency**	**Duration**	**Annual Cost**	**Hours**	**Frequency**	**Duration**	**Annual Cost**
Visual Inspection	0.5 hr	1/month	8 months[7]	$90	1 hr	1/month	8 months[7]	$181

Estimated cost for record retention

Facilities must retain records on site for a minimum of five years. The cost of complying with this provision is the cost of storing records. This cost is likely very low or close to zero.

Total compliance costs

This section presents the total costs of compliance for facilities under the Industrial Stormwater General Permit.

[7] Ecology requires inspections for all 12 months, but the Federal MSGP requires inspections 4 times per year, so we have analyzed the additional 8 inspections.

Table 11: Total Compliance Costs for Industrial Stormwater Permit Holders

Total Compliance Costs for Industrial Stormwater Permit Holders					
Sector	**SIC**	**Small**		**Large**	
		Low	**High**	**Low**	**High**
Refuse Systems	4953	$532	$973	$1,065	$1,898
Sawmills and Planning Mills, General	2421	$559	$1,000	$1,119	$1,952
Airports, Flying Fields, and Airport Terminal Services	4581	$496	$937	$995	$1,828
Prepared Fresh or Frozen Fish and Seafood	2092	$559	$1,000	$1,119	$1,952
Scrap and Waste Material	5093	$845	$1,286	$1,691	$2,524
Hazardous Waste: Treatment, Storage & Disposal	4953	$791	$1,232	$1,583	$2,416

Conclusion of estimated costs

The cost-to-sales ratios fall as sales rise. Ecology concluded, based on this result, that *the general permit has a disproportionate impact on small businesses.*

However, two points are important to keep in mind with regard to this conclusion.

1. At its highest, the permit represents 0.075% of average sales or 7.5 cents per $100.
2. The underlying factor is that permit compliance costs do not scale up in line with the size of a business. The numbers presented in this analysis show the typical large business is 7 to 30 times larger than the typical small business. At the same time, while a large business will possibly require more sampling than a small one, it does not need 10 times as much. Therefore, it is difficult to avoid disproportionate costs for smaller businesses and still assure compliance with the water quality standards.

Table 12 shows the cost-to-sales ratio for typical state Industrial Stormwater Permit compliance costs as a percentage of midrange annual sales for both small and large businesses for each sector.

Table 12: Cost-to-Sales Ratio for Small and Large Businesses Industrial Stormwater Permit Holders

Cost-to-Sales Ratio for Small and Large Businesses Industrial Stormwater Permit Holders							
		Midrange Sales		**Small**		**Large**	
Sector	**SIC**	**Small**	**Large**	**Low**	**High**	**Low**	**High**
Refuse Systems	4953	$2,480,800	$35,271,443	0.021%	0.039%	0.003%	0.005%
Sawmills and Planning Mills, General	2421	$2,758,934	$44,683,484	0.020%	0.036%	0.003%	0.004%
Airports, Flying Fields, and Airport Terminal Services	4581	$1,250,256	$42,130,674	0.040%	0.075%	0.002%	0.004%
Prepared Fresh or Frozen Fish and Seafood	2092	$3,489,539	$51,885,274	0.016%	0.029%	0.002%	0.004%
Scrap and Waste Material	5093	$2,518,394	$27,855,305	0.034%	0.051%	0.006%	0.009%
Hazardous Waste: Treatment, Storage & Disposal	4953	$2,927,390	$20,466,441	0.027%	0.042%	0.008%	0.012%

Chapter 4: Mitigation of Disproportionate Impacts

If the compliance cost ratio is higher for small businesses than for large businesses, then small businesses are disproportionately impacted. Ecology concluded in Chapter 3 that this is the case for the reissued NPDES General Permit for Industrial Stormwater.

The general permit rule (WAC 173-226-120) requires that disproportionate economic impacts of general permits on small businesses be reduced, when it is both legal and feasible to do so.

Legality and feasibility are determined by the legal context of existing state and federal regulations, such as the State Water Pollution Control Act (Chapter 90.48 RCW) and the federal Clean Water Act. Cost impacts on small businesses are reduced by modifying the conditions of the permit.

Mitigation involves one or more of the following:

- Establishing differing compliance or reporting requirements or timetables for small businesses.
- Clarifying, consolidating, or simplifying the compliance and reporting requirements under the general permit for small businesses.
- Establishing performance rather than design standards.
- Exempting small businesses from parts of the general permit.

Ecology amended the general permit to mitigate its impacts on small businesses as follows.

The new permit removes the requirements for:

- New operations to submit Stormwater Pollution Prevention Plans (SWPPPs) to Ecology during the permit application process.
- Facilities to submit Level 1, 2, or 3 Source Control Reports to Ecology.
- Facilities to perform extensive and specific sampling criteria.
- Facilities to conduct total copper and total lead sampling/analysis if total zinc levels exceeded the limit for two consecutive quarters.
- Facilities to submit a Notice of Termination when they receive a Conditional No Exposure exemption.
- Facilities to conduct oil and grease sampling and lab analysis and replaces it with the requirement for a visual assessment of "oil sheen."
- Existing facilities (in operation prior to the effective date of the permit) to complete public notice requirements during the permit process.

The new permit gives:

- Facilities the option to request a modification of coverage to:
    - Get an extension of time to complete required corrective actions.
    - Receive an exemption from installing additional structural source control and/or treatment BMPs.
- Small businesses 3 years to ensure the personnel who conduct site inspections are trained and certified–large businesses have two years to comply with this requirement.
- Facilities the ability to incorporate other plans into SWPPPs.

- An exemption for sampling and analysis with the demonstration of "consistent attainment" of benchmarks.

Mitigation measures must comply with state and federal requirements.

The general permit rule requiring Economic Impact Analysis (WAC 173-226-120) states that mitigation only needs to be undertaken when it is legal and feasible in meeting the stated objectives of the federal Clean Water Act, and Chapter 90.48 RCW, the State Water Pollution Act. This provision is an important restriction. If a proposed mitigation measure violates federal law or regulations, or if it violates state statute or rules, then it cannot be undertaken.

The conditions of the general permit based on federal regulations are requirements of federal law. Significant mitigation of these conditions would be a violation of federal NPDES program regulations, which establish effluent standards. Because these conditions are a consequence of federal law, they cannot be mitigated, and the compliance costs associated with them cannot be reduced. The general permit must contain effluent limits that are at least as strict as federal effluent standards, to mitigate their impact on small businesses.

Conditions required to meet the AKART requirement of the state Water Pollution Control Act (Chapter 90.48 RCW) are also legal requirements that Ecology cannot allow permit holders to violate. Thus, compliance costs based on the AKART requirement also cannot be mitigated.

Ecology also places conditions in general permits to ensure discharges do not violate the state surface water quality, ground water quality, or sediment management standards (173-200, 173-201, 173-204, 173-224 WAC). These conditions are legal requirements that Ecology cannot allow permit holders to violate. Compliance costs associated with these permit conditions cannot be mitigated.

The above circumstances severely limit Ecology's ability to reduce cost impacts on small businesses. Only costs imposed by permit conditions that are stricter than those required by the above laws can be legally mitigated. Because, for the most part, the permit simply contains conditions needed to comply with these laws, usually only minor mitigation measures can legally be undertaken. The cost reductions that result are usually small.

Impact of mitigation on effectiveness of general permit

The general permit rule states mitigation only needs to be undertaken when it is legal and feasible in meeting the stated objectives of the Clean Water Act and Chapter 90.48 RCW, the State Water Pollution Control Act. Even if a proposed mitigation measure is legal, if it would limit the general permit's effectiveness in controlling water pollution too much, it should not be undertaken.

Ecology has reduced the cost of the permit where possible. Reducing costs does not remove the disproportionate impact. The size of the facilities' impermeable surface, nature of the industrial activity, and installation and maintenance of best management practices determines the quantity and quality of the stormwater discharge. Given this, there is no reason to believe small businesses will have a small stormwater impact simply because they have fewer employees. Therefore, there is no basis that would allow Ecology to be more lenient on small businesses without an unreasonable risk of violating federal or state water quality laws and rules.

A discharge of pollutants to receiving water requires a permit. If Ecology issues a general permit that allows people to harm the quality of the water receiving the discharge then Ecology would be in violation of state and federal law. Ecology hopes the benchmarks coupled with the adaptive management strategy in the general permit will allow dischargers to meet water quality standards without excessive costs. Nonetheless, the elements in the following section can potentially reduce the cost of the permit. Most of the mitigation presented is not only for small businesses, but applies to all facilities and therefore will benefit small businesses as well.

Mitigation measures in the new general permit

SWPPP submittal requirement

The permit no longer requires facilities to submit Stormwater Pollution Prevention Plans (SWPPPs) to Ecology as part of the permit application process. This is intended to reduce the burden and time delays associated with getting coverage under the general permit.

The completeness or accuracy of the SWPPP is a permit compliance issue and is not necessary to determine if a facility should be covered under the general permit. The permit still contains the ability for Ecology, local governments, and the public to obtain a copy of a permittee's SWPPP to assess the facility's compliance with the SWPPP permit conditions.

Public notice requirement

The permit no longer requires existing, but previously unpermitted, facilities to complete public notice requirements during the permit application process. This change is consistent with WAC 173-226-130(5), which requires unpermitted facilities to complete public notice requirements only if they meet the definition of a "new operation". WAC 173-226-030(16) defines new operation as "an operation that begins activities that result in a discharge, or potential discharge to waters of the state, on or after the effective date of the general permit."

Sampling

The permit no longer includes complex criteria for when stormwater samples may be collected. This will reduce the burden on permitted facilities, which were previously required to track weather information to ensure that the collected samples meet the criteria for sampling. In some cases, this change will allow facilities to collect their own samples, instead of hiring a consulting firm to track weather conditions and collect samples.

Total copper and lead analysis

The permit no longer contains the requirement for total copper and total lead sampling/analysis to be conducted in future discharges if total zinc was exceeded for two consecutive quarters.

Quarterly oil and grease sampling

The permit removed the requirement for all facilities to conduct quarterly oil and grease sampling and lab analysis. This requirement has been replaced with the requirement for a quarterly visual assessment to determine if stormwater has a "visible oil sheen."

Consistent attainment

The permit allows suspension from certain sampling and analysis parameters when facilities receive "consistent attainment" of benchmark values during eight consecutive samples. Consistent attainment on any given set of monitoring parameters exempts the facility from sampling and analysis on that particular set of parameters for the remaining term of the permit.

Time extensions and exemptions for facilities subject to corrective actions

The permit requires facilities that exceed the benchmarks multiple times to perform escalating levels of pollution prevention measures (i.e., install additional BMPs, with a goal of meeting benchmarks in future discharges). These BMPs need to be installed within specified timeframes to remain in compliance with the permit. The new permit includes a mechanism that allows facilities to request an extension to install the necessary structures.

In addition, the facility may request an exemption from having to install additional BMPs, if the additional BMPs are not feasible or not necessary to prevent violations of water quality standards. When requested, Ecology may grant time extensions or waivers if site-specific information supports the request, and the extension or waiver is approved through a modification of permit coverage per WAC 173-226-200(3)(f).

Corrective actions documented with SWPPP revisions rather than Level 1, 2 and 3 source control reports

The new permit changes the way facilities document the completion of corrective actions. Specifically, the permit no longer requires facilities to submit Level 1, 2, or 3 Source Control Reports to Ecology. The new permit requires facilities to make appropriate revisions to the SWPPP and certify that the SWPPP is consistent with the permit and applicable stormwater management manual.

At Levels 1 and 2, the revised SWPPP would be kept on site, except at Level 3, the revised SWPPP must be submitted to Ecology.

Incorporation of plans in SWPPP

The new permit allows facilities to incorporate, by reference, other plans (or portions of plans) prepared for other purposes at their facility. This reduces the potential burden that would occur if a facility had to restate or duplicate portions of plans that were already required for compliance with different regulations or laws. For example, portions of the Pollution Prevention Plan prepared under the Hazardous Waste Reduction Act, Chapter 70.95C RCW, could simply be referenced (rather than physically restated or duplicated) to comply with the Industrial Stormwater General Permit.

Training and certification

The new permit requires facilities to ensure that site inspection and visual monitoring are done by personnel who have completed a training and certification program. The permit allows 3 years for small businesses to comply with this training and certification requirement, and 2 years for permittees who don't meet the definition of small business (50 or fewer employees).

Notice of termination

The new permit removed the requirement for facilities to submit a Notice of Termination when they receive a Conditional No Exposure exemption. This removes an administrative burden on facilities, and ensures that permit related costs are cancelled as soon as possible after receiving a Conditional No Exposure exemption.

Western Washington Hydrology Model
Version 3.0

User Manual

August 2006

Western Washington Hydrology Model
Version 3.0

User Manual

Prepared by
Clear Creek Solutions, Inc.

August 2006

To download the Western Washington Hydrology Model
and the electronic version of this user's manual,
please visit our website at:
http://www.ecy.wa.gov/programs/wq/stormwater/wwhm_training/wwhm/wwhm_v3/index.html.

If you have questions about the WWHM, please contact:
Foroozan Labib, Environmental Engineer
Department of Ecology
Water Quality Program
(360) 407-6439
flab461@ecy.wa.gov

If you require this document in an alternative format, please call the secretary at (360) 407-6401. The TTY number is 711 or 1-800-833-6388.

Table of Contents

INTRODUCTION

The WWHM3 is the third edition of the Western Washington Hydrology Model. It was designed by the Washington State Department of Ecology, AQUA TERRA Consultants, and Clear Creek Solutions, Inc. (the successor to the Washington offices of AQUA TERRA Consultants). This version is faster, more flexible, easier, and offers more options than WWHM2. Because of its increased flexibility the user can now model almost any hydrologic condition related to stormwater control and design.

This user manual and development of WWHM3 was funded by the Washington State Department of Ecology Contract No. C0500104 with AQUA TERRA Consultants. AQUA TERRA staff (and now Clear Creek Solutions staff) responsible for the WWHM3 and this user manual are Joe Brascher, Shanon White, and Doug Beyerlein.

Purpose

The purpose of the WWHM3 is to size stormwater control facilities to mitigate the effects of increased runoff (peak discharge, duration, and volume) from proposed land use changes that impact natural streams, wetlands, and other water courses.

The WWHM3 provides:

- A uniform methodology for the 19 counties of Western Washington
- A more accurate methodology than single event design storms
- An easy-to-use software package

The WWHM3 is based on:

- Continuous simulation hydrology (HSPF)
- Actual long-term recorded precipitation data
- Measured pan evaporation data
- Historic vegetation (for Predeveloped conditions)
- Regional HSPF parameters

Parameter values can be modified for local conditions.

What's New in Version 3

WWHM3 gives the user greater modeling flexibility and options. Version 2 was limited to drainages of less than half a square mile (320 acres) because of the lack of a conveyance feature (natural channel or pipe). This limitation does not apply to WWHM3; with Version 3 the user can model entire watersheds of unlimited size as long as they are contained within a single county.

Specific changes and additions in Version 3 include:

- Icons are now called elements in the Schematic screen.
- There are separate elements for trapezoidal ponds, irregular ponds, tanks, and vaults.

- Basin land use categories now include land slopes (flat, moderate, and steep).
- Runoff credits have been replace with specific categories to disperse roof runoff to lawn, etc.
- Standard residential has been removed, although the user can still explicitly input the standard residential assumptions.
- Two lateral basins (pervious and impervious) have been added. Flow can go directly from a lateral basin to another basin without a connecting conveyance system.
- A flow splitter now offers greater flexibility in deciding how to separate the flow.
- The open channel conveyance element has been added.
- Gravel trench beds have been added.
- Wetponds have been added. Wetponds can be used to model wetlands and areas influenced by high groundwater.
- There is no longer a Point of Compliance icon (or element). The user can specify a point of compliance at any element by right clicking on that element and selecting "Point of Compliance". There can be multiple points of compliance. The model keeps track of each one.
- There is no longer an Extender icon (or element). The user now explicitly links one element to another.
- Preferences has been replaced by View, Options and a criteria checker has been added.
- View/Export Time Series has been moved into Tools and additional options have been added.

Computer Requirements

- Windows 2000/XP with 150 MB uncompressed hard drive space
- Internet access (only required for downloading WWHM3, not required for executing WWHM3)
- Pentium 3 or faster processor (desirable)
- Color monitor (desirable)

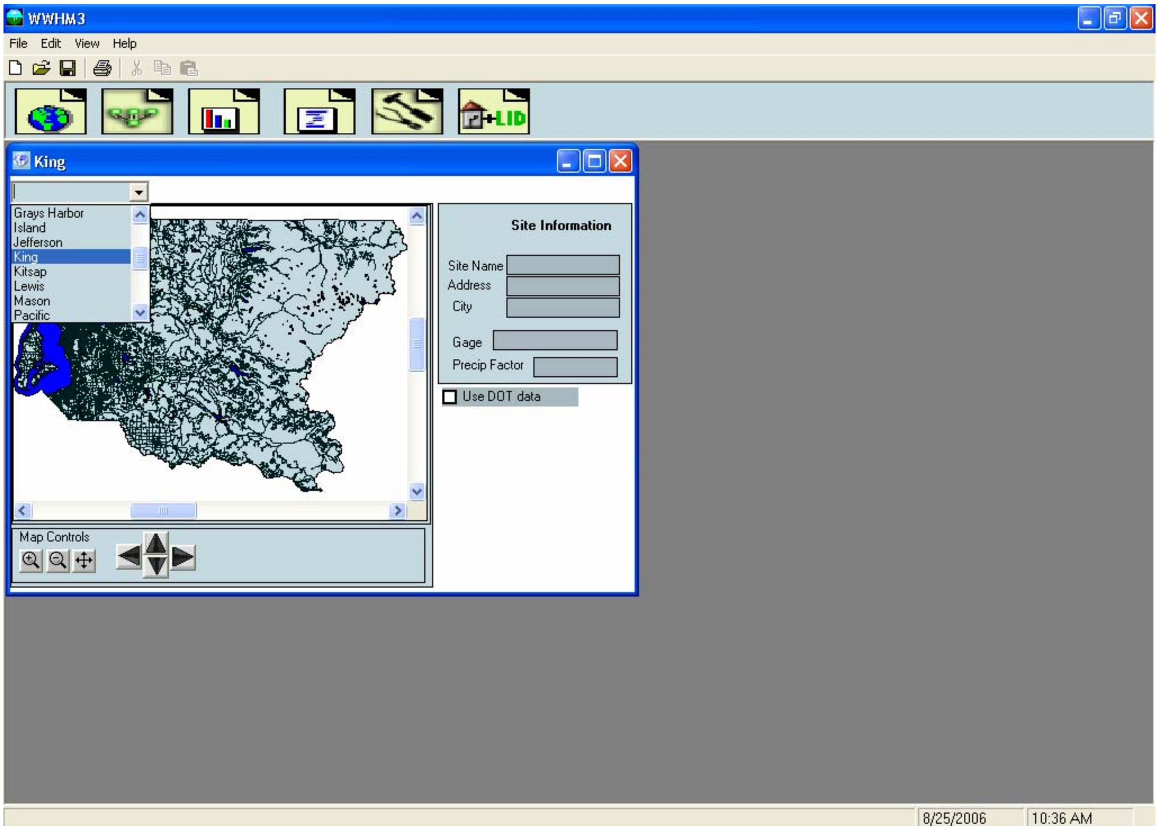
Before Starting the Program

- Knowledge of the site location and/or street address.
- Knowledge of the actual distribution of existing site soil by category (A/B, C, or saturated).
- Knowledge of the planned distribution of the proposed development (buildings, streets, sidewalks, parking, lawn areas) overlying the soil categories.
- An idea of a first approximation of the top surface area for a trapezoidal or irregular-shape pond (if used).

QUICK START

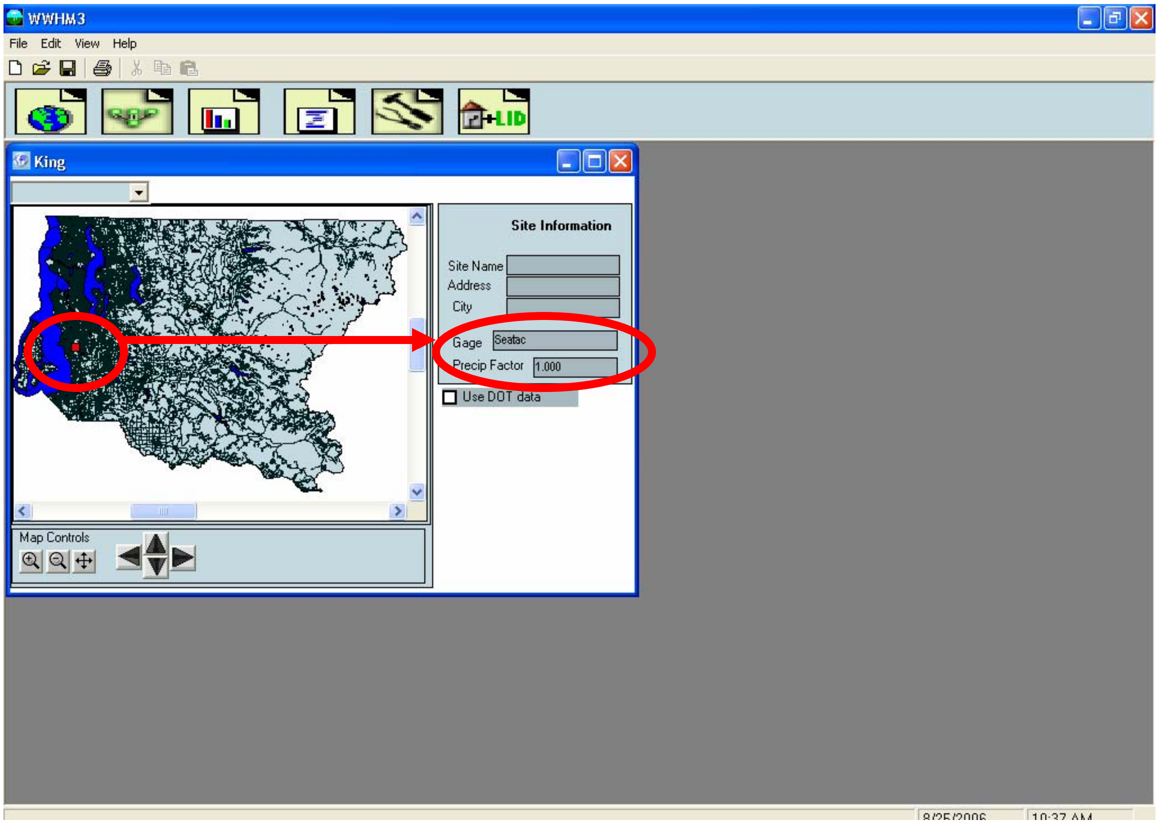
Below is a brief set of steps that show how to use the WWHM3 to quickly size a stormwater detention pond.

1. Select the county in which the project site is located.



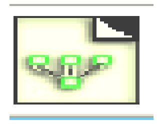
Click the down arrow in the box in the upper left corner. A list of all 19 Western Washington counties is shown. Scroll down to find the county you want. Left click on the county name. The county map will then show on the map screen.

Locate the project site on the map. Use the map controls to magnify a portion of the map, if needed. Select the project site by left clicking on the map location. A red square will be placed on the map identifying the project site.

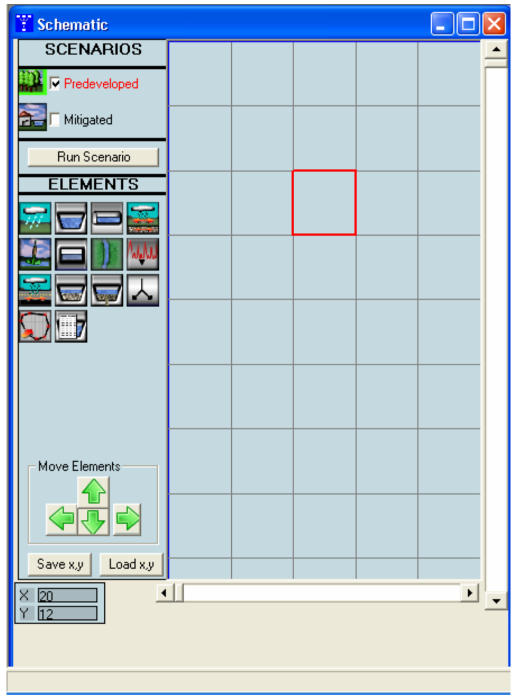


The WWHM3 selects the appropriate rain gage record and precipitation multiplication factor.

2. Use the tool bar (immediately above the map) to move to the Scenario Editor. Click on the General Project Information button.



The General Project Information button will bring up the Schematic Editor.



The schematic editor screen contains two scenarios: Predeveloped and Mitigated.

Set up first the Predeveloped scenario and then the Mitigated scenario.

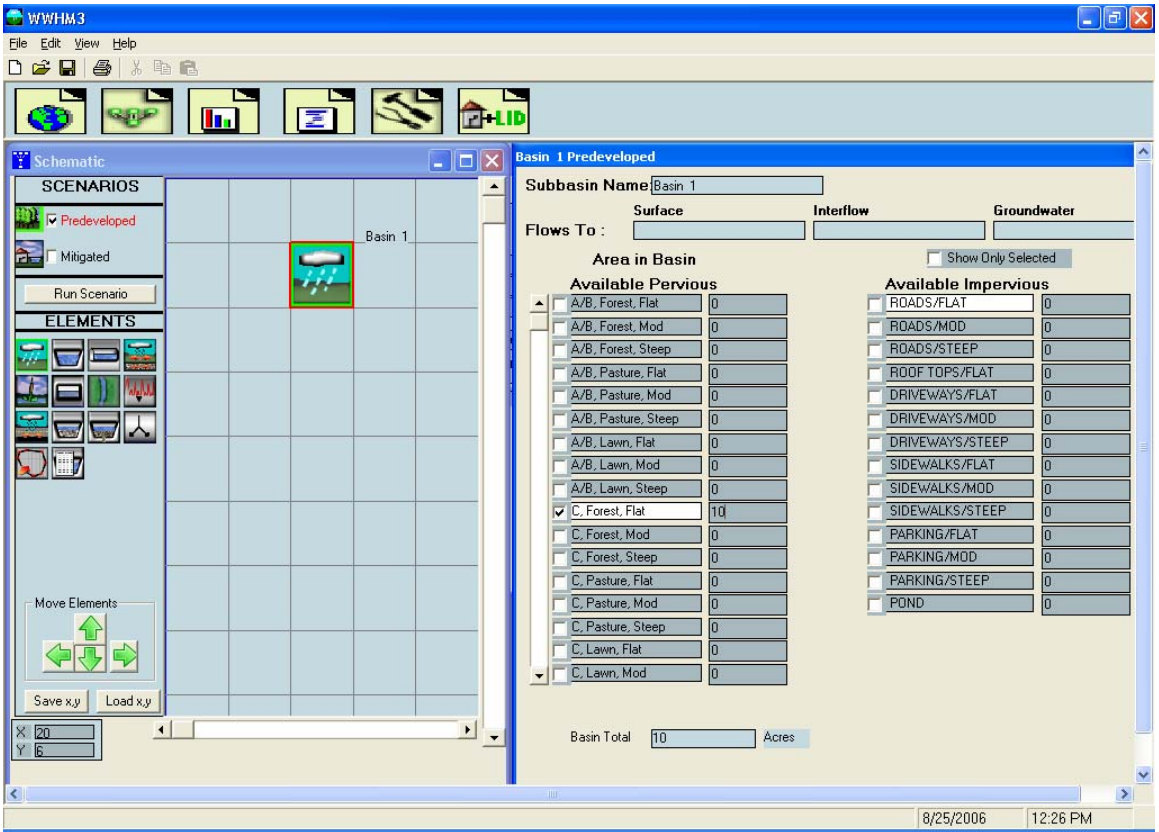
Check the Predeveloped scenario box.

Left click on the Basin element under the Elements heading. The Basin element is the upper left element.

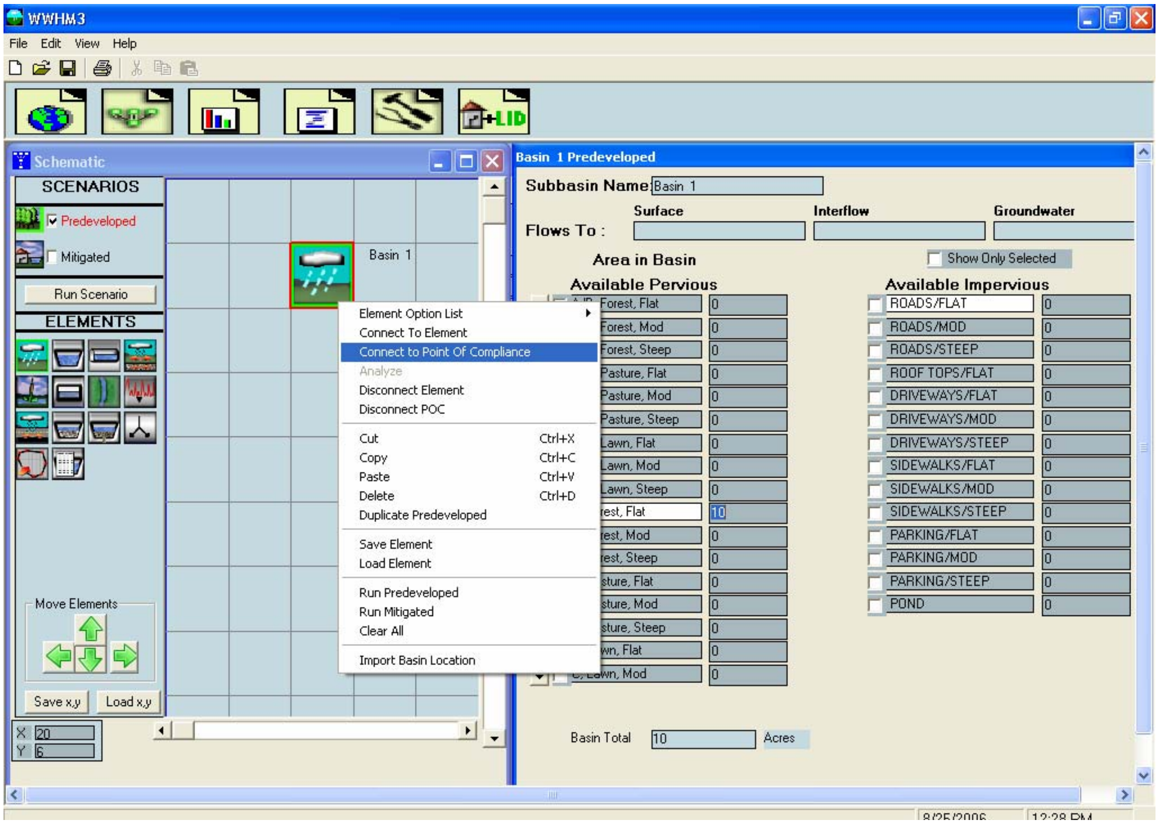
Select any grid cell (preferably near the top of the grid) and left click on that grid. The basin will appear in that grid cell.

The entire grid can be moved up, down, left, or right using the Move Elements arrow buttons.

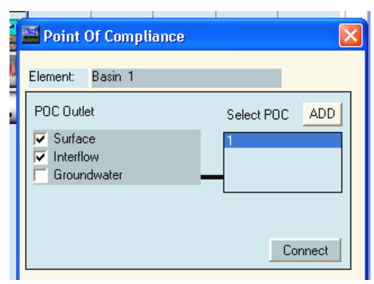
The gird coordinates from one project can be saved (Save x,y) and used for new projects (Load x,y).



To the right of the grid is the land use information associated with the basin. Select the appropriate soil, vegetation, and land slope for the Predeveloped scenario. For this example we will assume that the Predeveloped land use is 10 acres of C soil (till) with forest vegetation, on a flat (0-5%) slope.

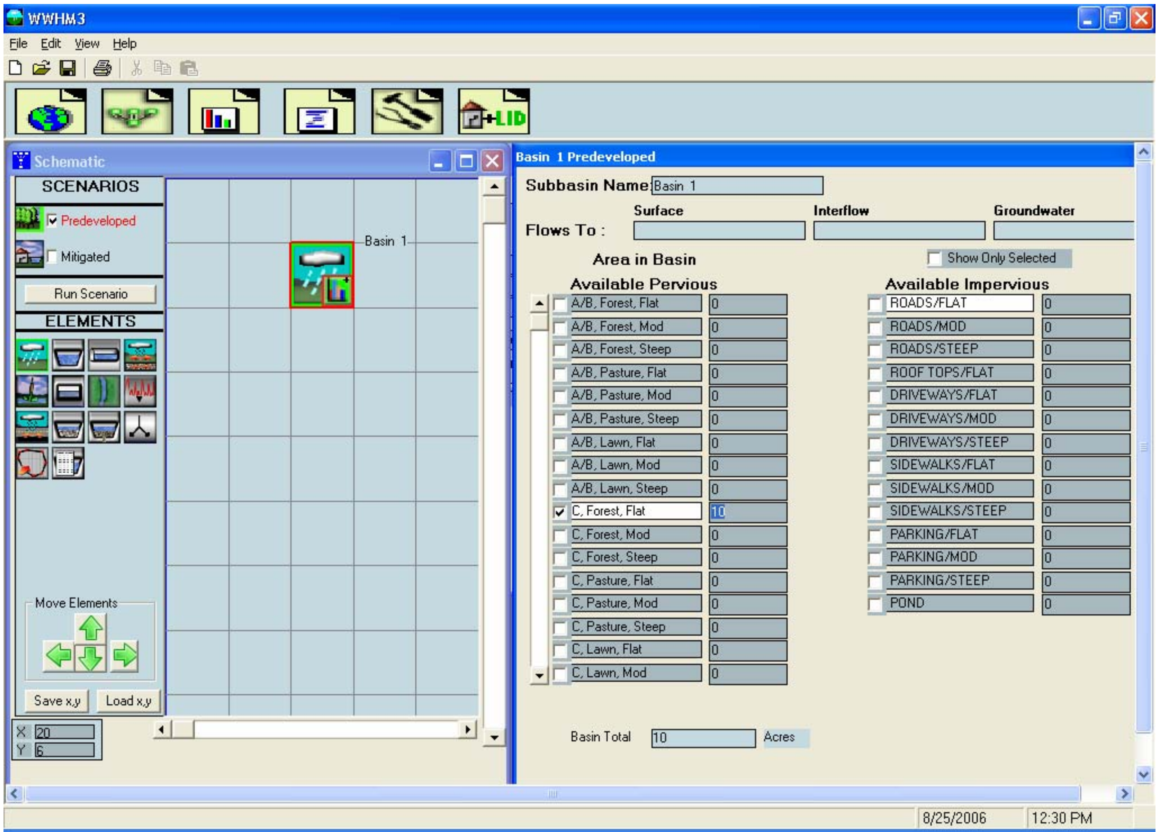


The exit from this basin will be selected as our point of compliance for the Predeveloped scenario. Right click on the basin element and highlight Connect to Point of Compliance.



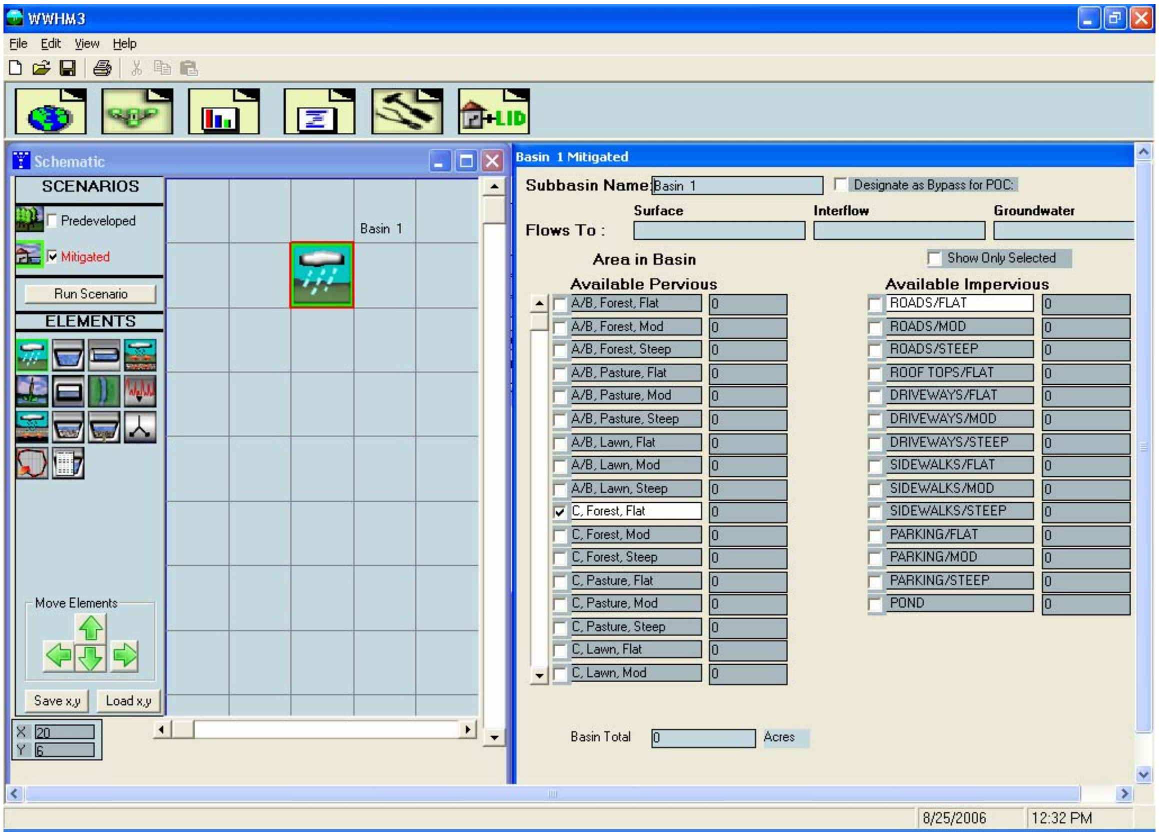
The Point of Compliance screen will be shown for Predeveloped Basin 1. The POC (Point of Compliance) outlet has been checked for both surface runoff and interflow. These are the two flow components of stormwater runoff. Do not check the groundwater box unless there is observed and documented base flow on the project site.

Click the Connect button in the low right corner to connect this point of compliance to the Predeveloped basin.

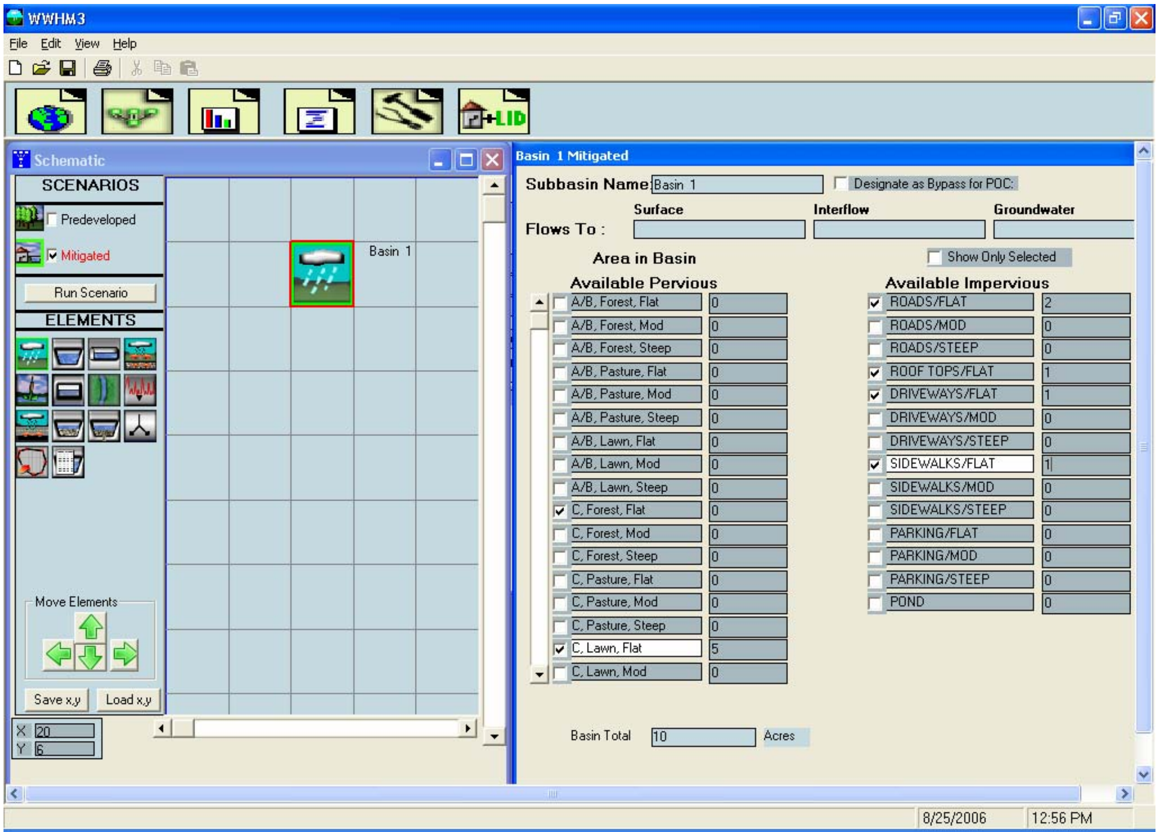


After the point of compliance has been added to the basin the basin element will change. A small box with a bar chart graphic will be shown in the lower right corner of the basin element. This small POC box identifies this basin as a point of compliance.

3. Set up the Mitigated scenario.



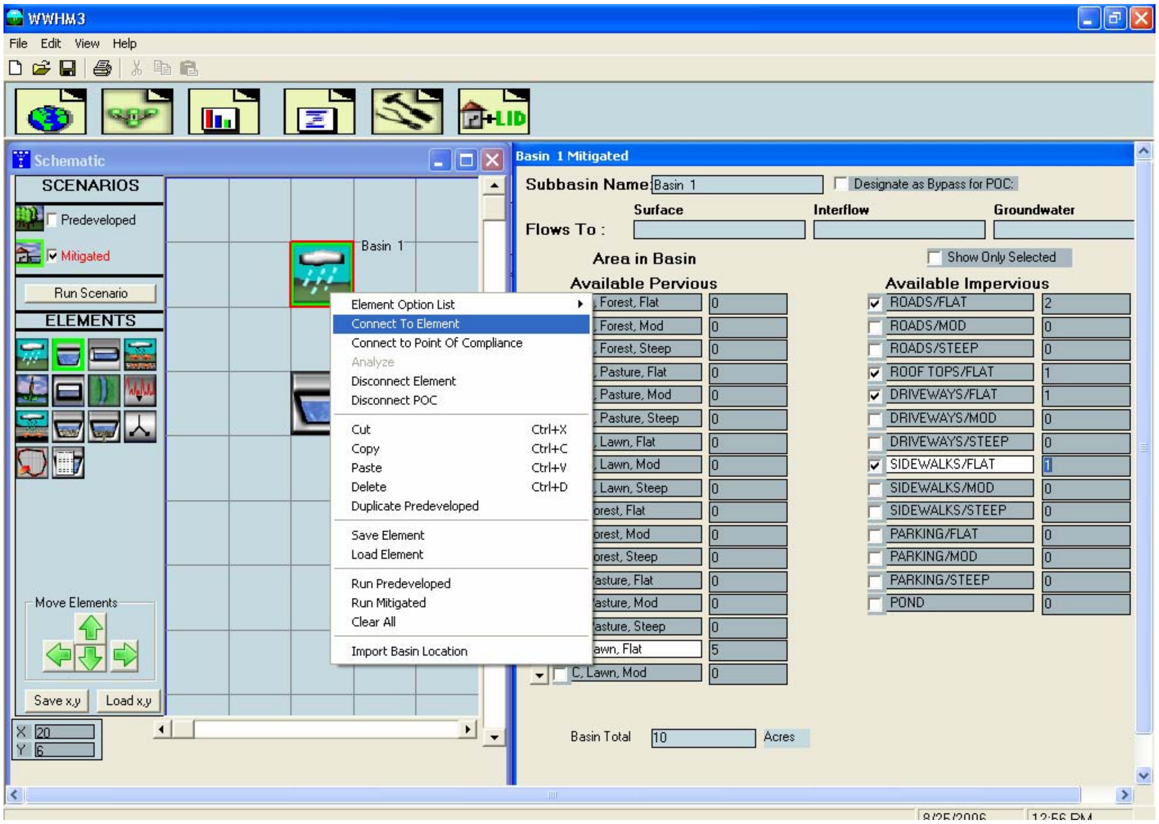
First, check the Mitigated scenario box and place a basin element on the grid.



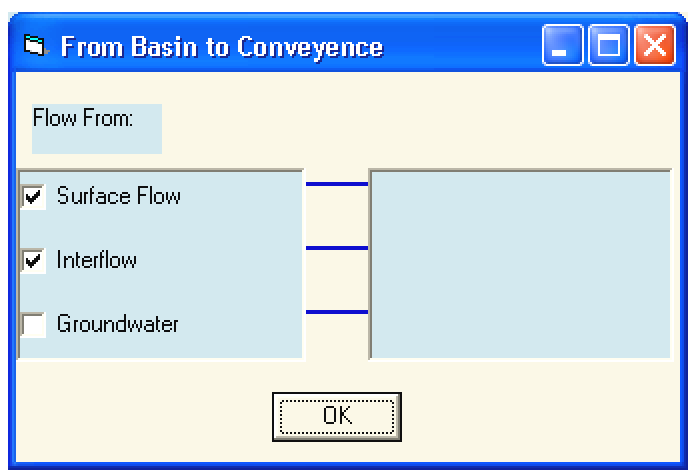
For the Mitigated land use we have:

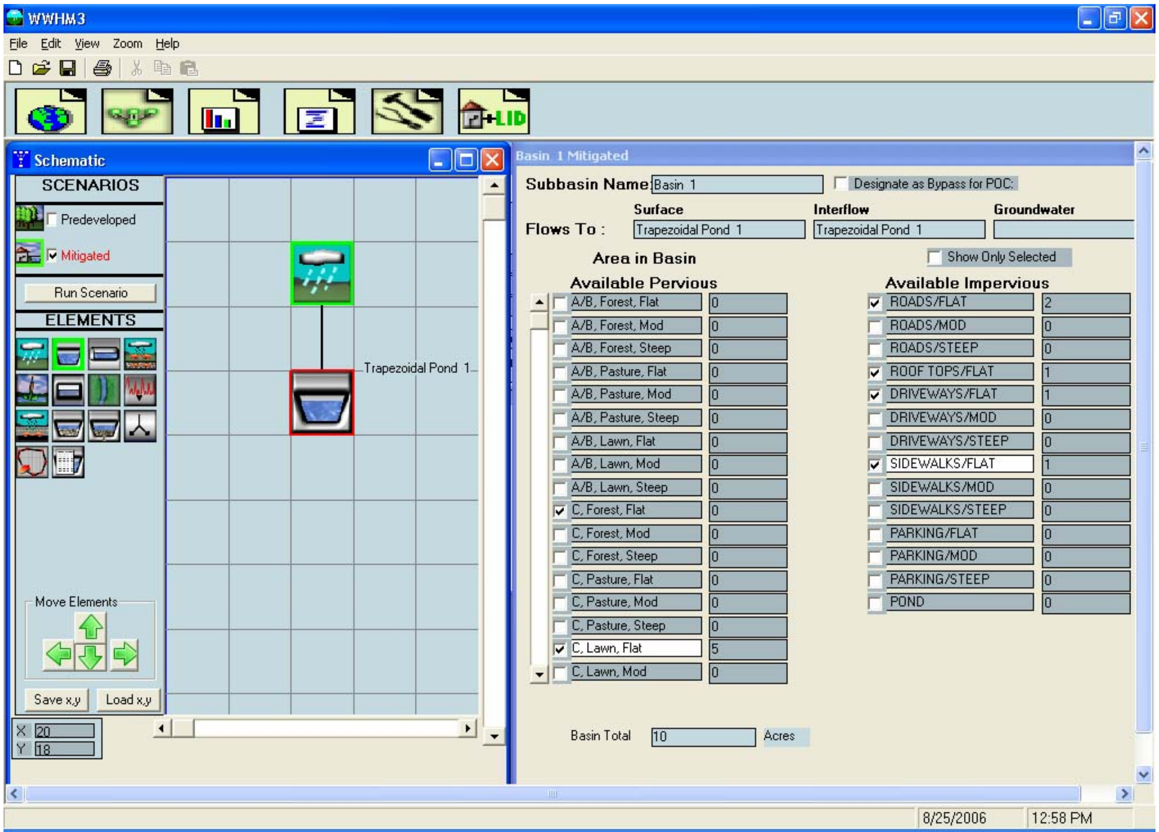
- 5 acres of C, lawn, flat
- 2 acres of roads, flat
- 1 acre of roof tops
- 1 acre of driveways, flat
- 1 acre of sidewalks, flat

We will add a trapezoidal pond downstream of the basin.

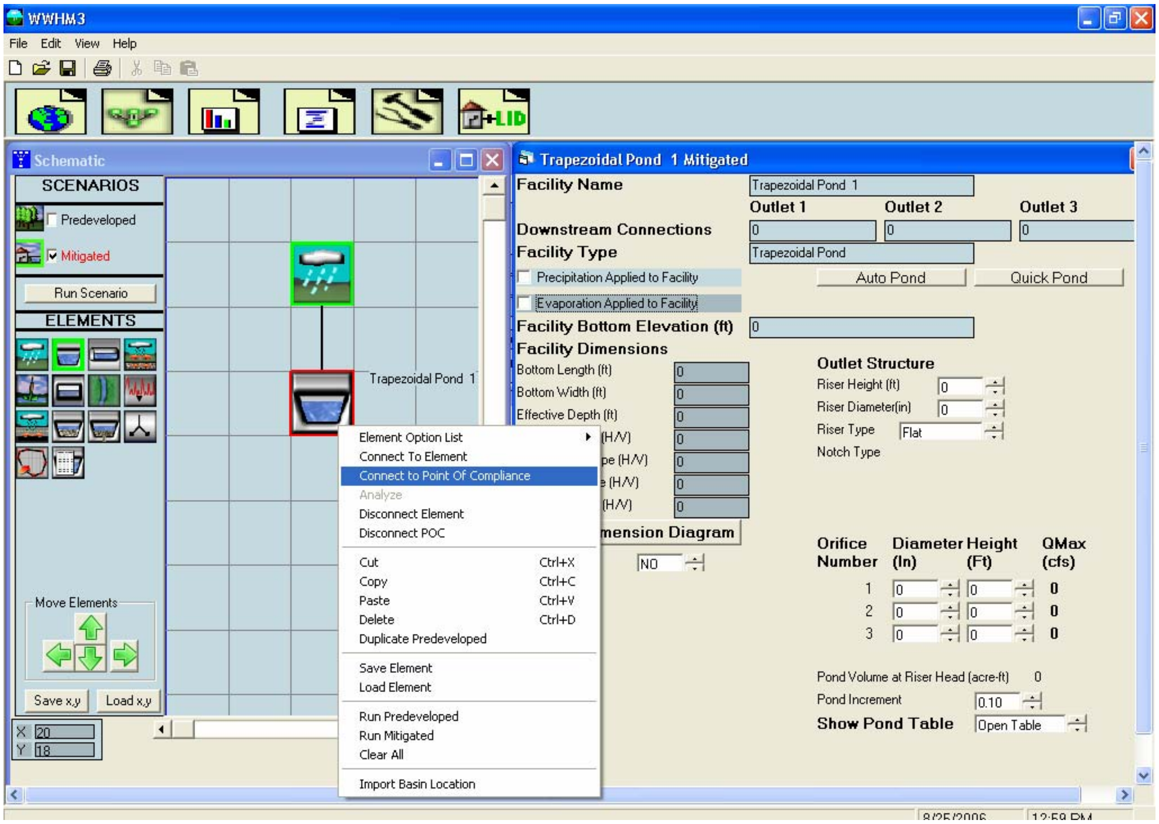


The trapezoidal pond element is placed below the basin element on the grid. Right click on the basin and select Connect To Element. A green line will appear with one end connected to the basin. With the mouse pointer pull the other end of the line down to the trapezoidal pond and click on the pond. This will bring up the From Basin to Conveyance screen. As with the Predeveloped scenario we want to only connect the surface flow and the interflow from the basin to the pond. Click OK.

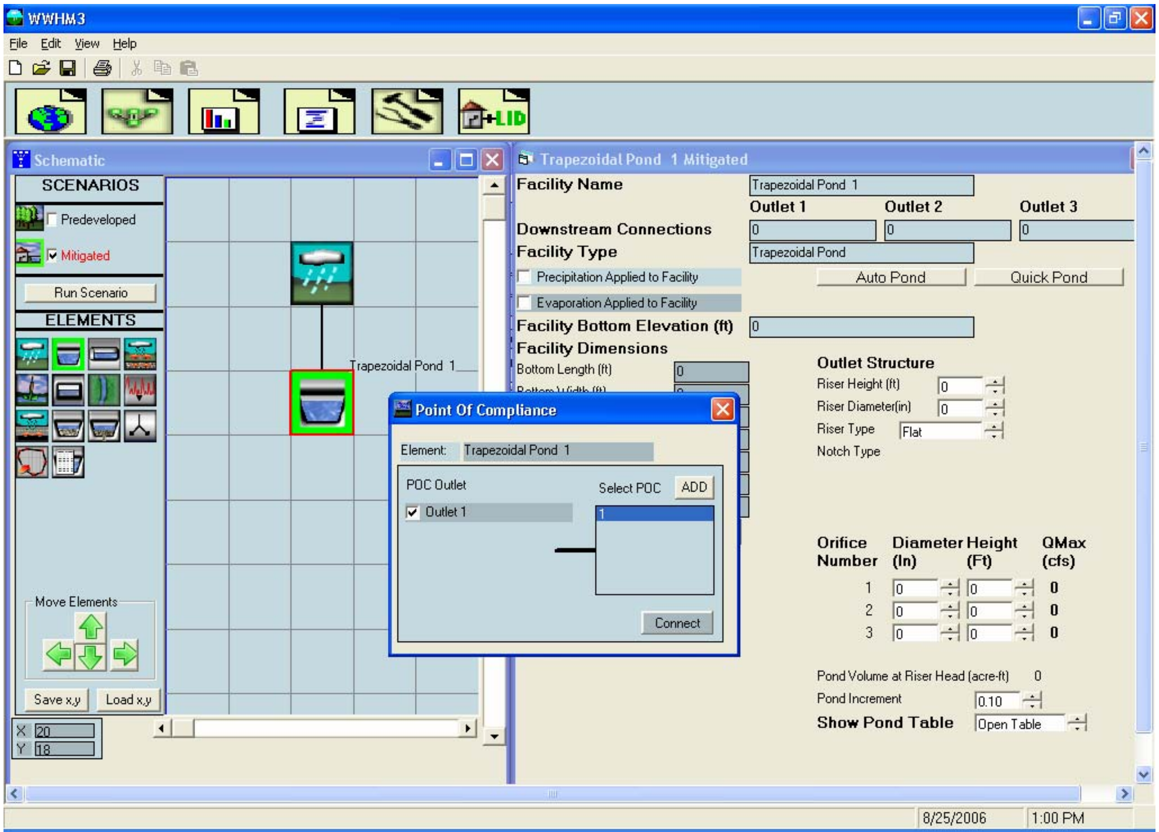




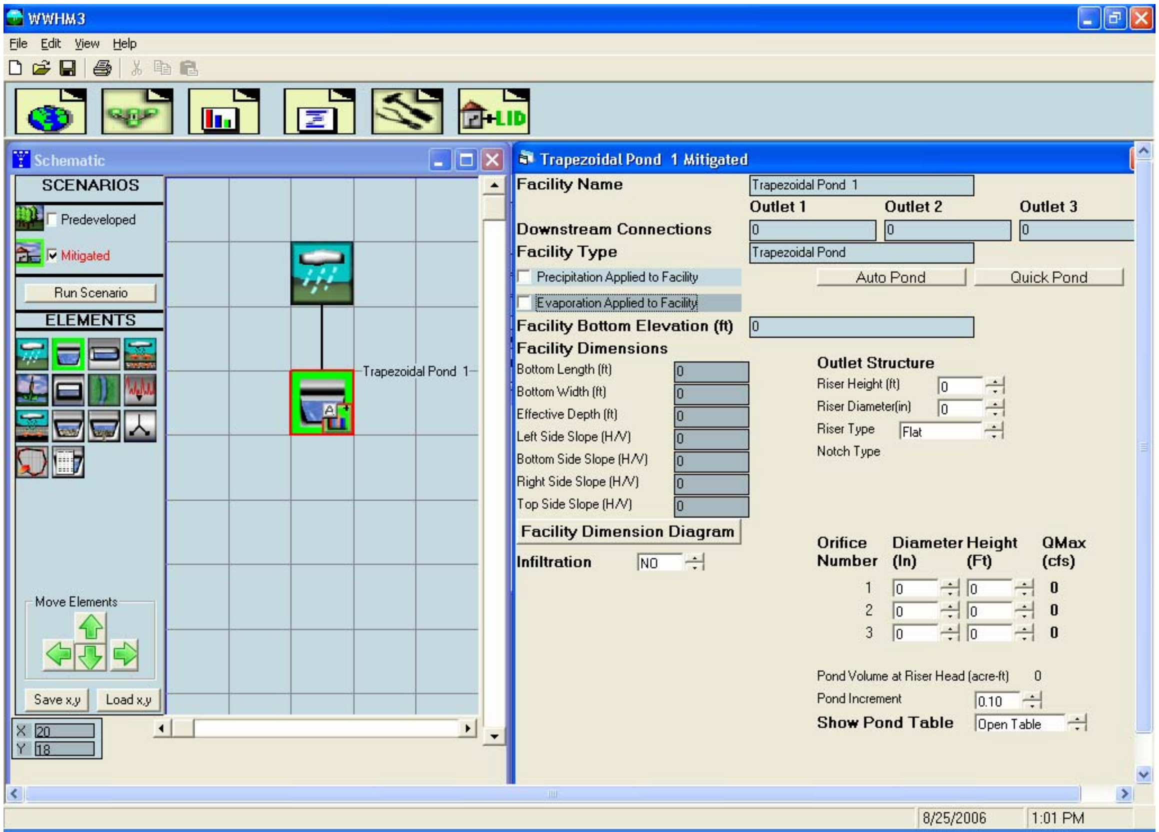
A line will connect the basin to the pond.



Right click on the trapezoidal pond element to connect the pond’s outlet to the point of compliance. Highlight Connect to Point Of Compliance and click.

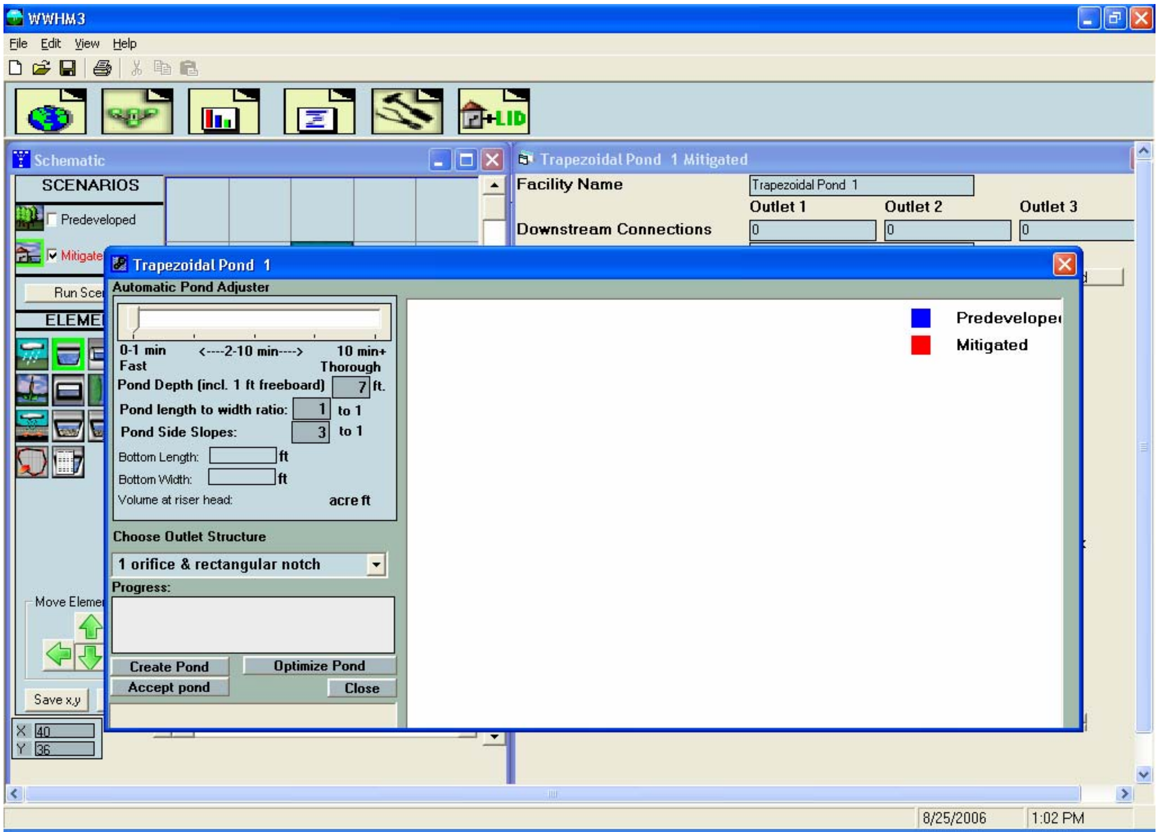


The Point of Compliance screen will be shown for the pond. The pond has one outlet (by default). The outflow from the pond will be compared with the Predeveloped runoff. The point of compliance is designated as POC 1 (WWHM3 allows for multiple points of compliance). Click on the Connect button.



The point of compliance is shown on the pond element as a small box with the letter "A" and a bar chart symbol in the lower right corner.

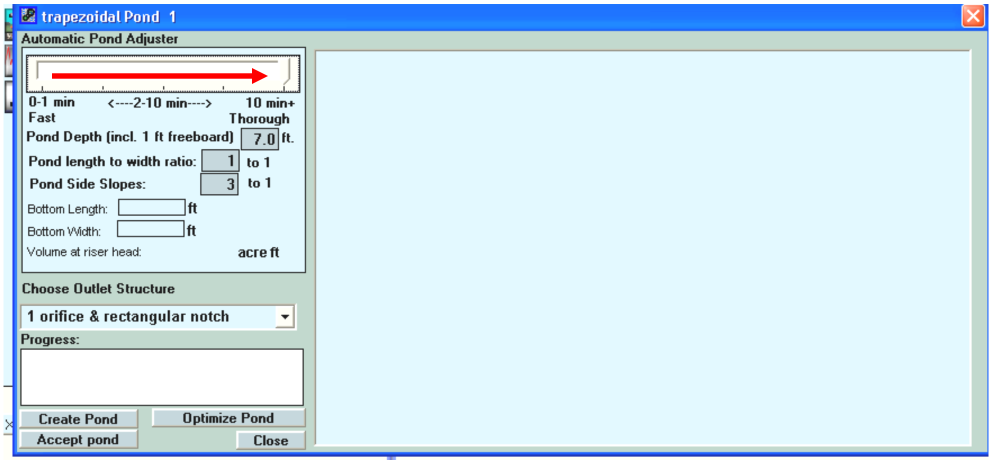
4. Sizing the pond.



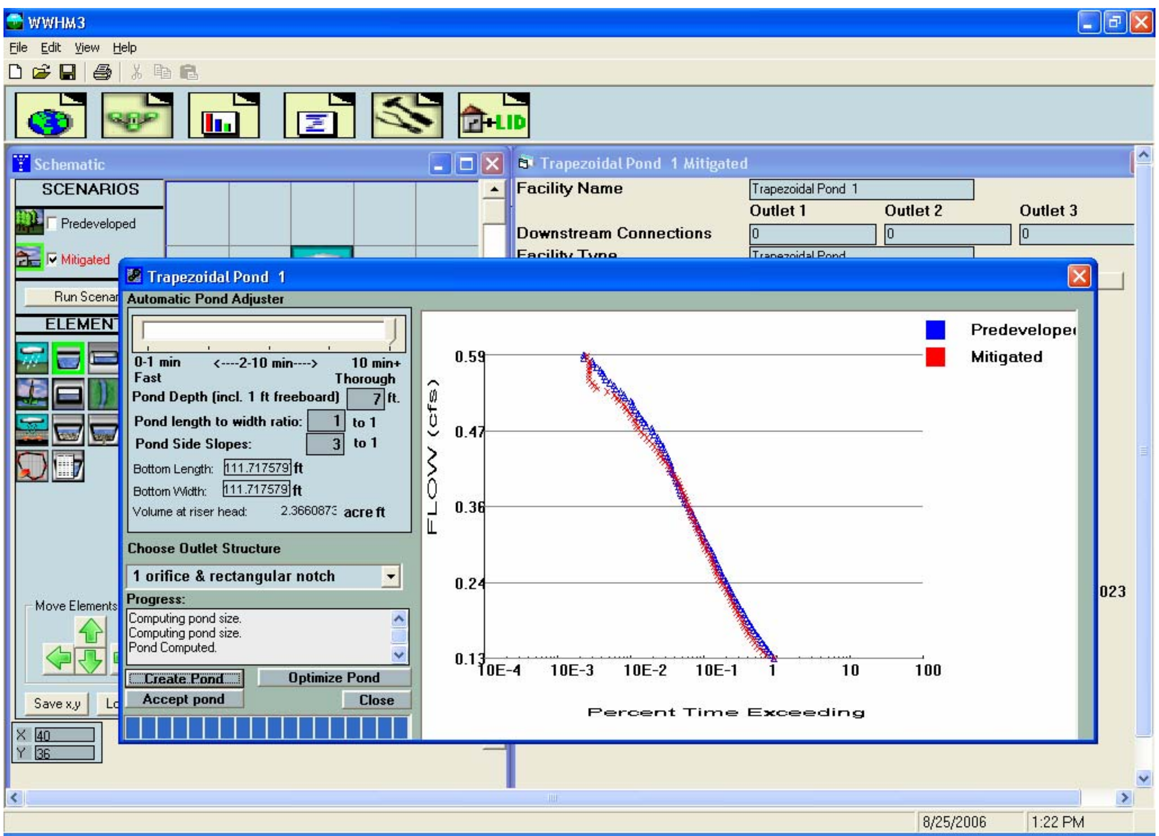
A trapezoidal stormwater pond can be sized either manually or automatically (using AutoPond). For this example AutoPond will be used.

Click on the AutoPond button and the AutoPond screen will appear. The user can set the pond depth (default: 7 feet), pond length to width ratio (default: 1 to 1), pond side slopes (default: 3 to 1), and the outlet structure configuration (default: 1 orifice and riser with rectangular notch weir).

To optimize the pond design and create the smallest pond possible, move the Automatic Pond Adjuster pointer from the left to the right.



The pond does not yet have any dimensions. Click the Create Pond button to create initial pond dimensions and optimize the pond size and outlet structure.



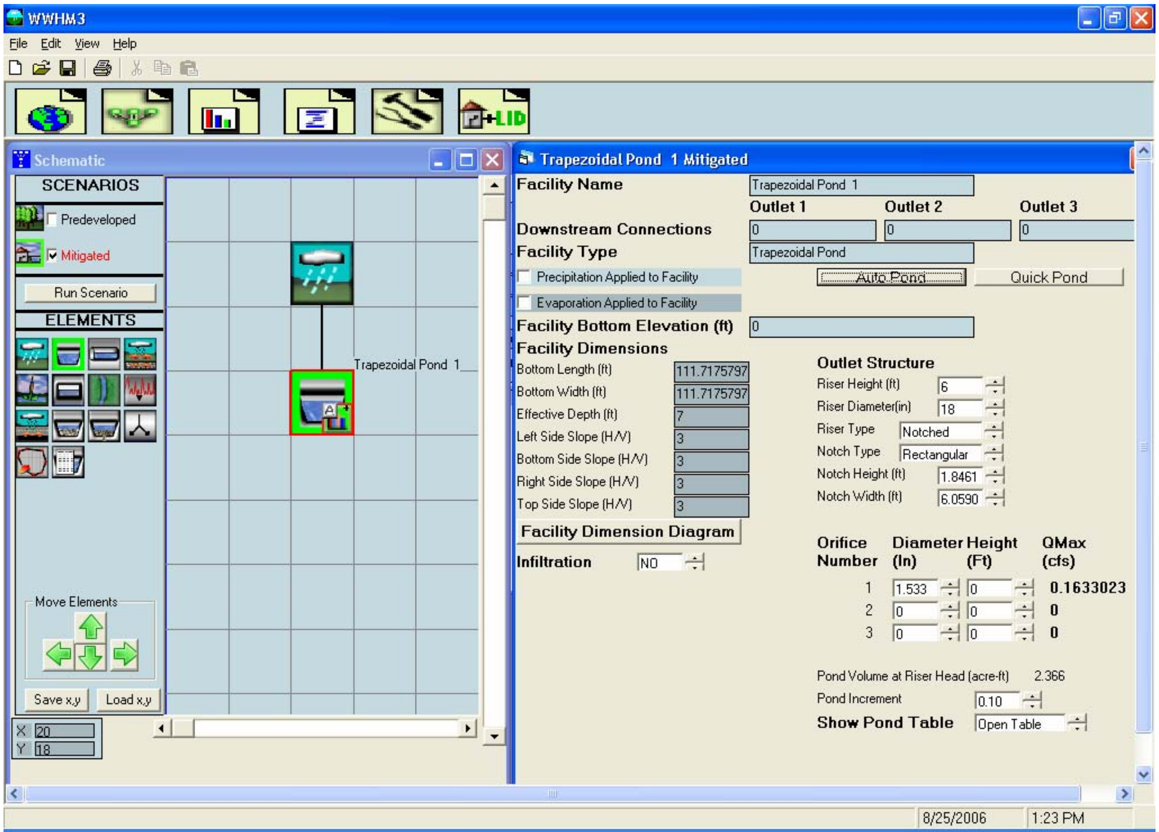
The WWHM3 first computes the Predeveloped runoff then the flow frequency for the Predeveloped runoff. From the flow frequency results half of the 2-year and the 50-year flows are identified. This is the range selected for the flow duration analysis. The

Predeveloped flow duration values between half of the 2-year and the 50-year are plotted on the screen in blue.

The WWHM3 computes Mitigated runoff. AutoPond selects initial pond and outlet structure dimensions and the Mitigated flow is routed through the pond. The outflow from the pond is analyzed and the Mitigated flow duration is plotted on the screen in red.

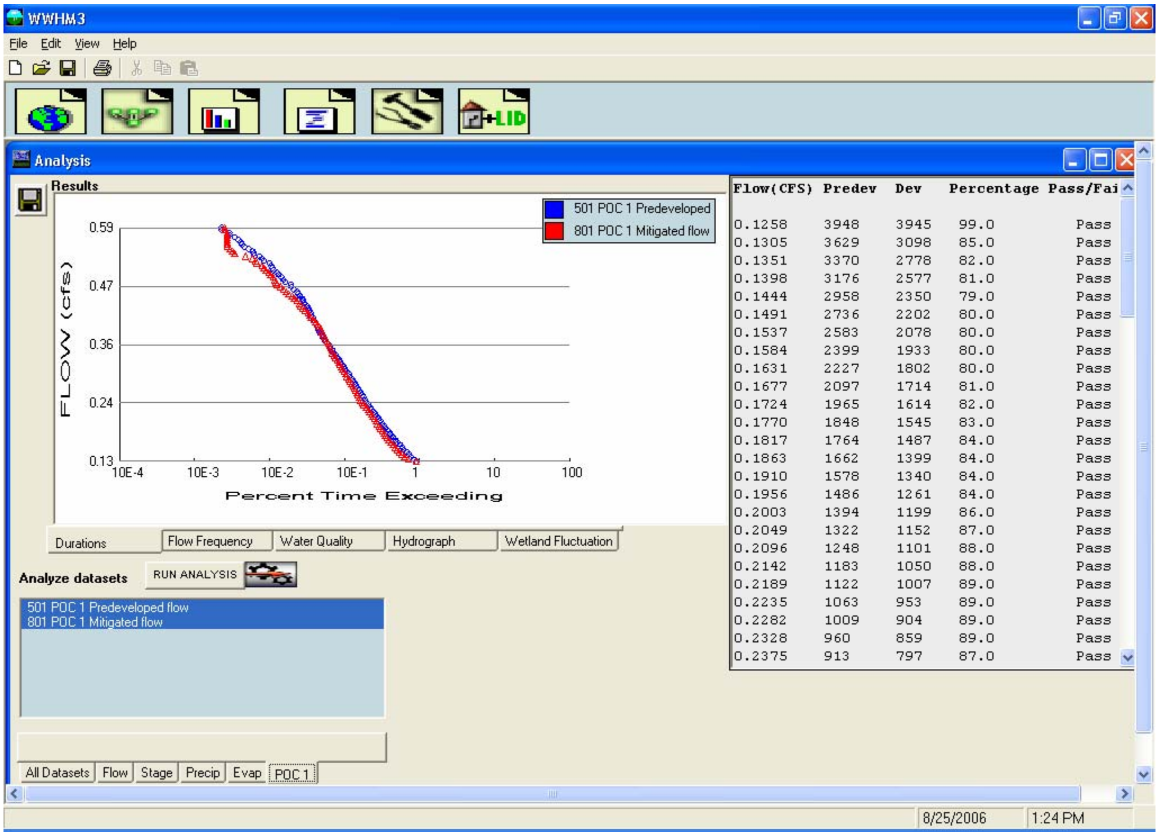
AutoPond compares the Mitigated flow duration results with the Predeveloped flow duration values. If the Mitigated flow duration values are greater than the Predeveloped values AutoPond increases the size of the pond or alters the outlet structure based on predefined rules and reruns the Mitigated runoff through the revised pond. If the Mitigated flow duration values are less than the Predeveloped values AutoPond decreases the size of the pond or alters the outlet structure and reruns the Mitigated runoff through the revised pond. Either way, AutoPond continues this exercise until the smallest possible pond is designed. At that point AutoPond announces that it is finished. The pond is now sized.

The user may continue to manually optimize the pond by manually changing pond dimensions and/or the outlet structure configuration. After making these changes the user should click on the Optimize Pond button to check the results and see if AutoPond can make further improvements.

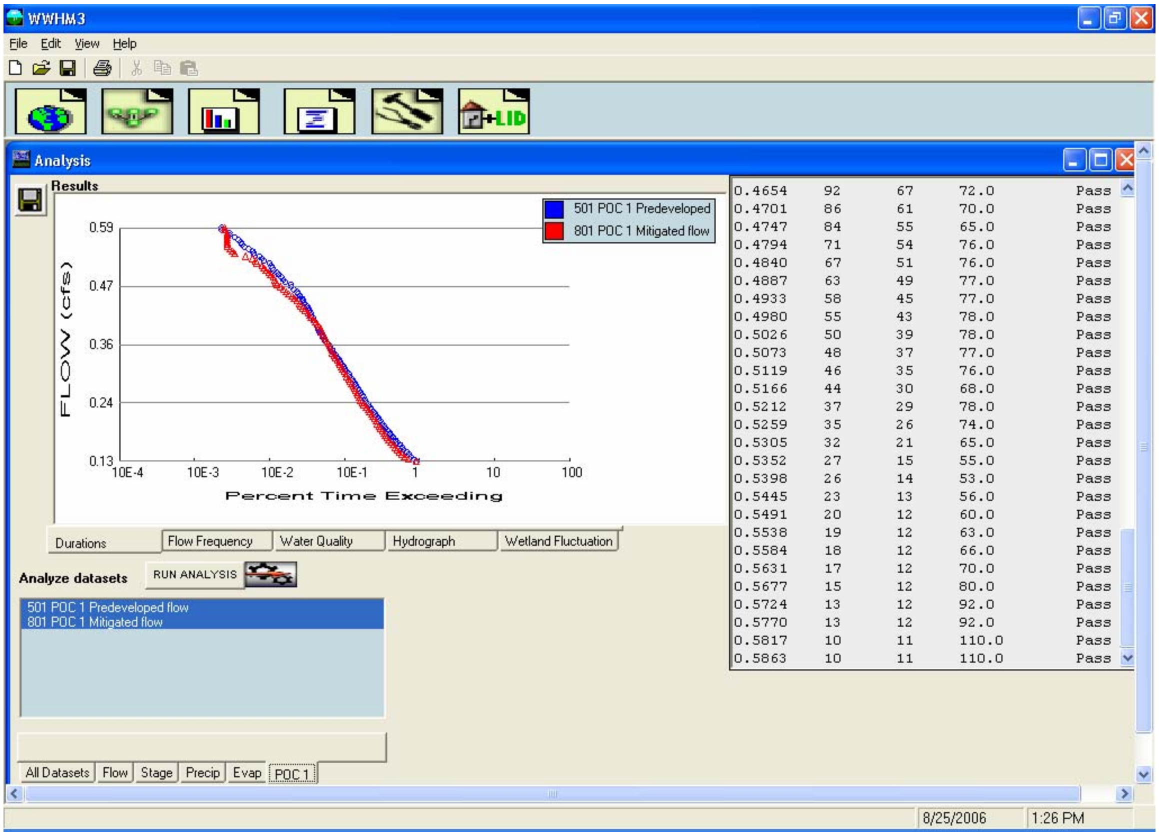


The final pond dimensions (bottom length, bottom width, effective pond depth, and side slopes) and outlet structure information (riser height, riser diameter, riser weir type, weir notch height and width, and orifice diameter and height) are shown on the trapezoidal pond screen to the right of the Schematic grid.

5. Review analysis.

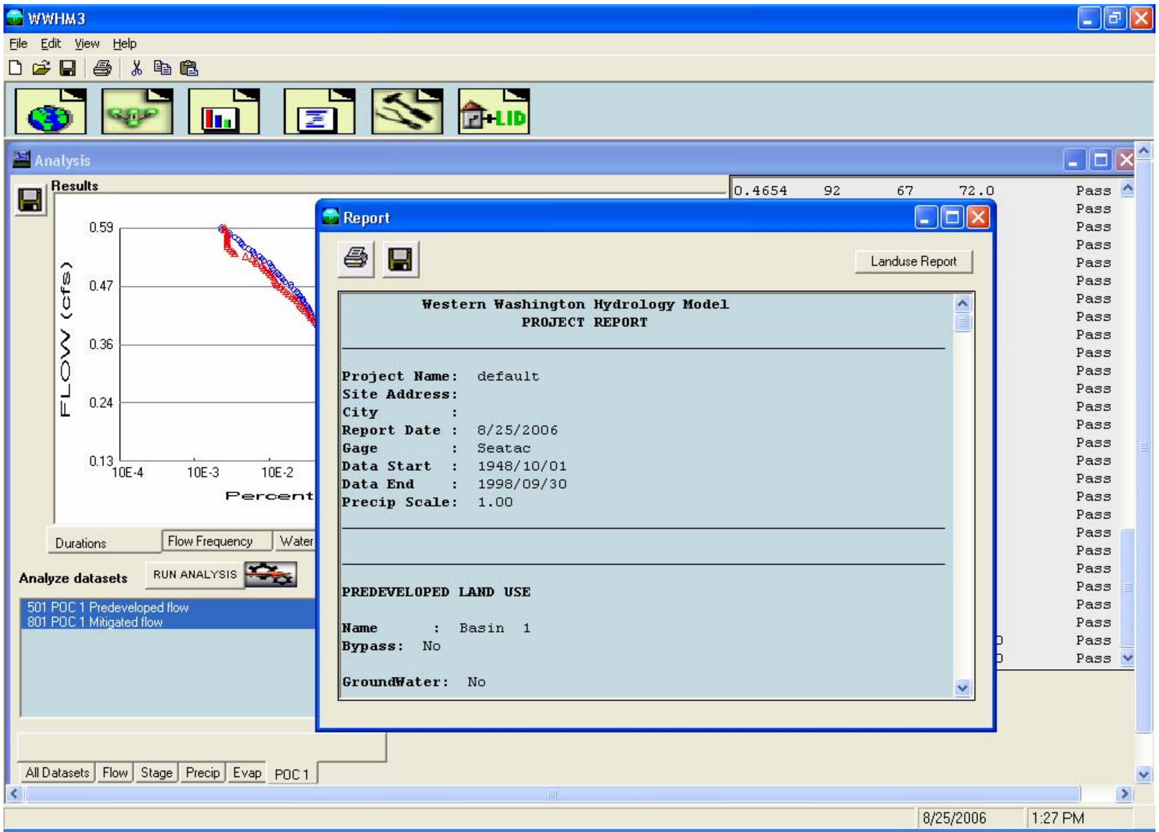


The Analysis tool bar button (third from the left) brings up the Analysis screen where the user can look at the results. Each time series dataset is listed in the Analyze Datasets box in the lower left corner. To review the flow duration analysis at the point of compliance select the POC 1 tab at the bottom and make sure that both the 501 POC 1 Predeveloped flow and 801 POC 1 Developed flow are highlighted. Click the Run Analysis button.

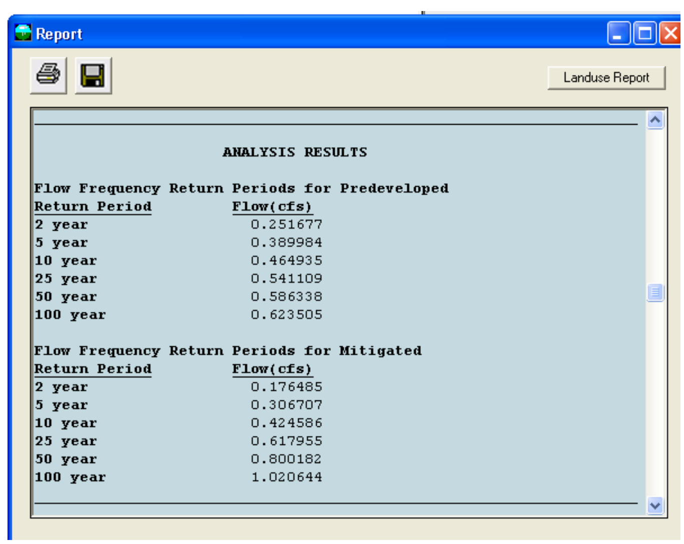


The flow duration plot for both Predeveloped and Mitigated flows will be shown along with the specific flow values and number of times Predeveloped and Mitigated flows exceeded those flow values. The Pass/Fail on the right indicates whether or not at that flow level the Ecology flow control standard criteria were met and the pond passes at that flow level (from half of the 2-year flow to the 50-year). If not, a Fail is shown; one Fail fails the pond design.

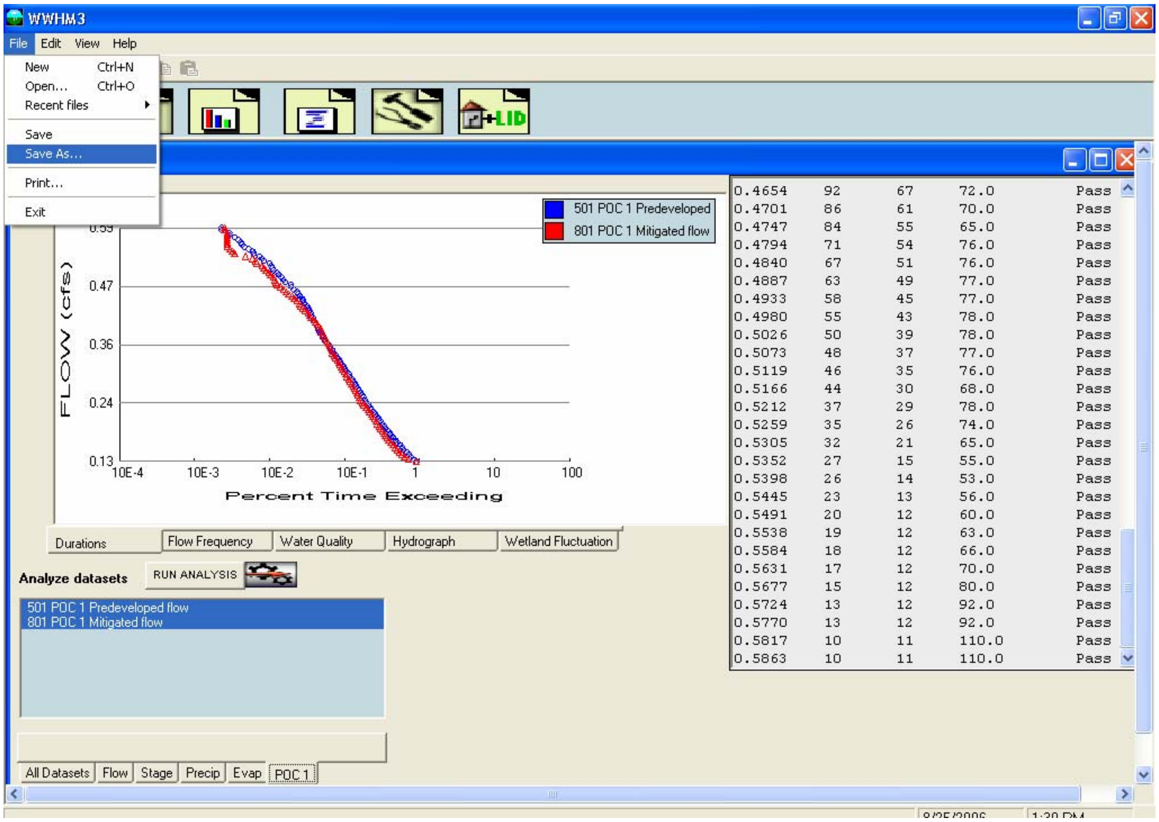
6. Produce report.



Click on the Reports tool bar button (fourth from the left) to generate a project report with all of the project information and results. Scroll down the Report screen to see all of the results.

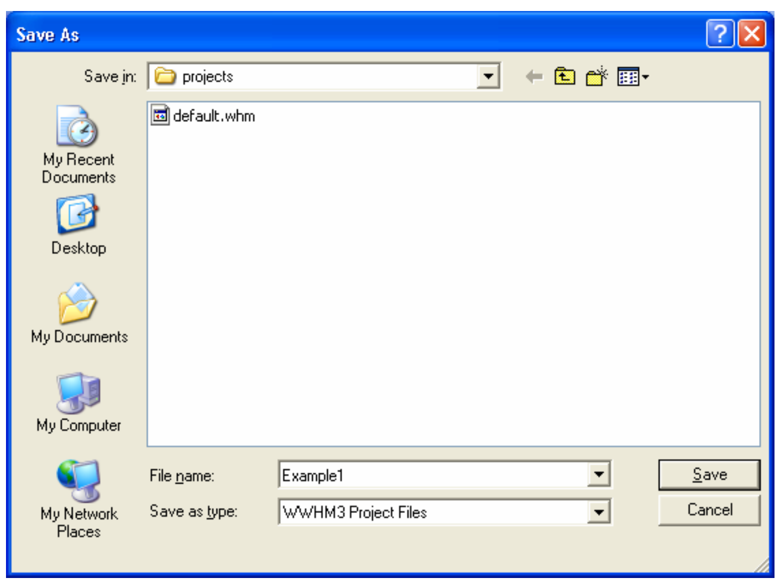


7. Save project.



To save the project click on File in the upper left corner and select Save As.

Select a file name and save the WWHM3 project file. The user can exit WWHM3 and later reload the project file with all of its information by going to File, Open.



MAIN SCREENS

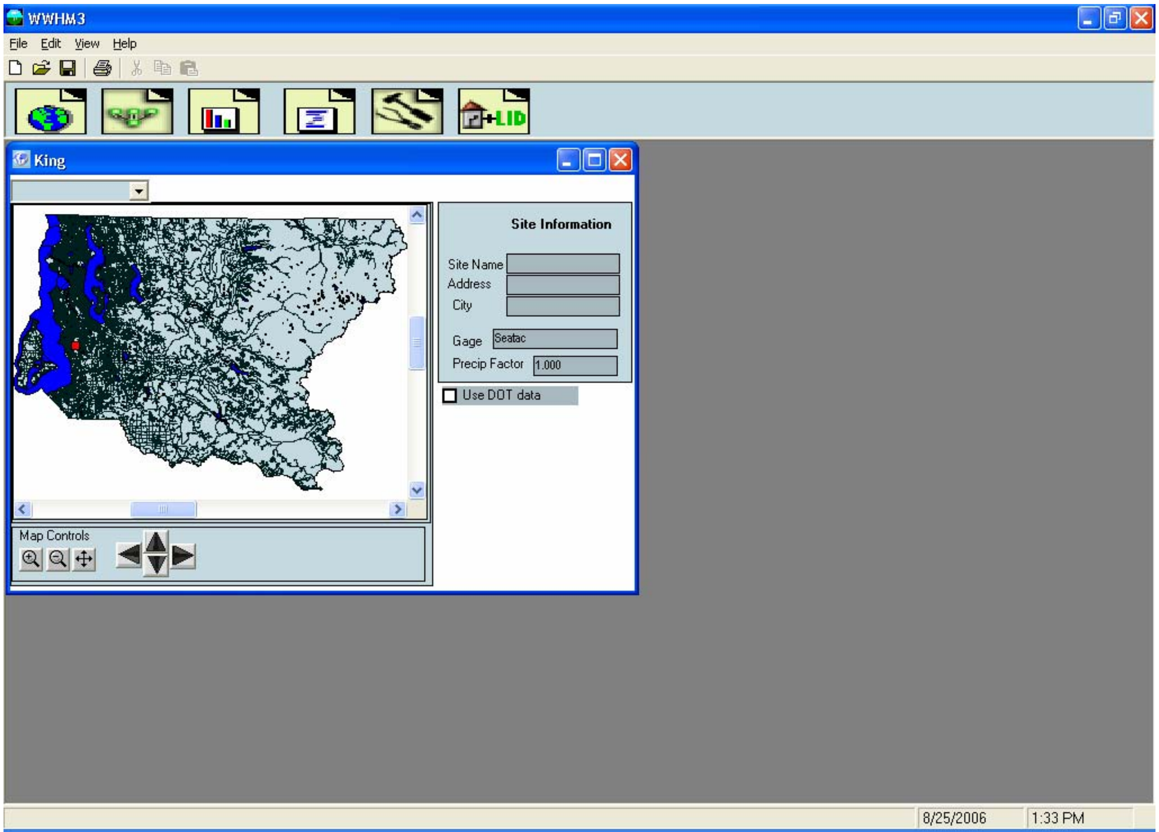
WWHM3 has six main screens. These main screens can be accessed through the buttons shown on the tool bar above or via the View menu.

The six main screens are:

- Map Information
- General Project Information
- Analysis
- Reports
- Tools
- LID (Low Impact Development) Analysis

Each is discussed in more detail in the following sections.

MAP INFORMATION SCREEN



The Map Screen contains county information. The map is directly linked to the meteorological database that contains precipitation and evaporation data. The precipitation gage and precip factor are shown to the right of the map. They change depending on the project site location.

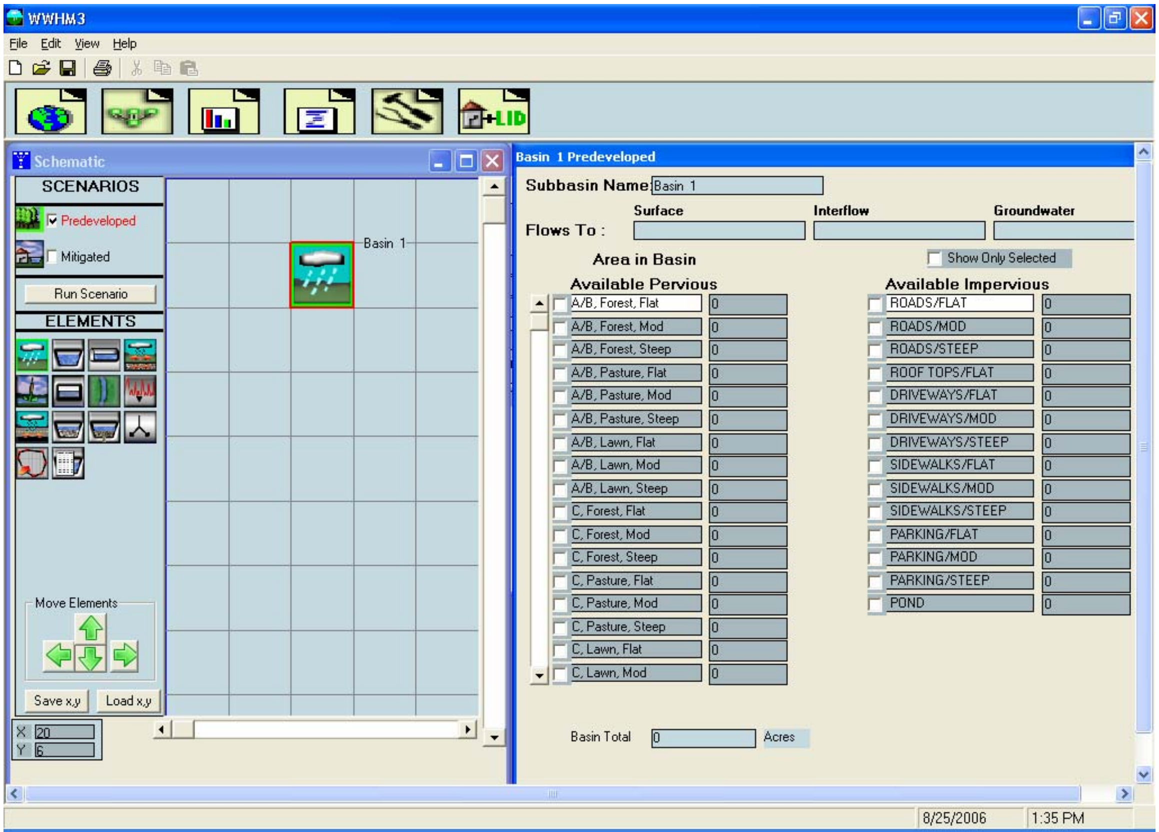
The user can elect to use Washington State Department of Transportation (DOT) precipitation data developed by MGS Consulting by checking the "Use DOT data" box to the right of the map. When the DOT data box is checked the map screen changes to show a map of the entire 19 counties of Western Washington with the area for which the DOT precipitation data are available outlined (the data are not available everywhere).

The county selection can be changed by clicking on the pulldown menu above the map and selecting one of the 19 Western Washington counties.

The user can provide site information (optional).

The user locates the project site on the map screen by using the mouse and left clicking at the project site location. Right clicking on the map re-centers the view. The + and – buttons zoom in and out, respectively. The cross hair button zooms out to the full county view. The arrow keys scroll the map view.

GENERAL PROJECT INFORMATION SCREEN



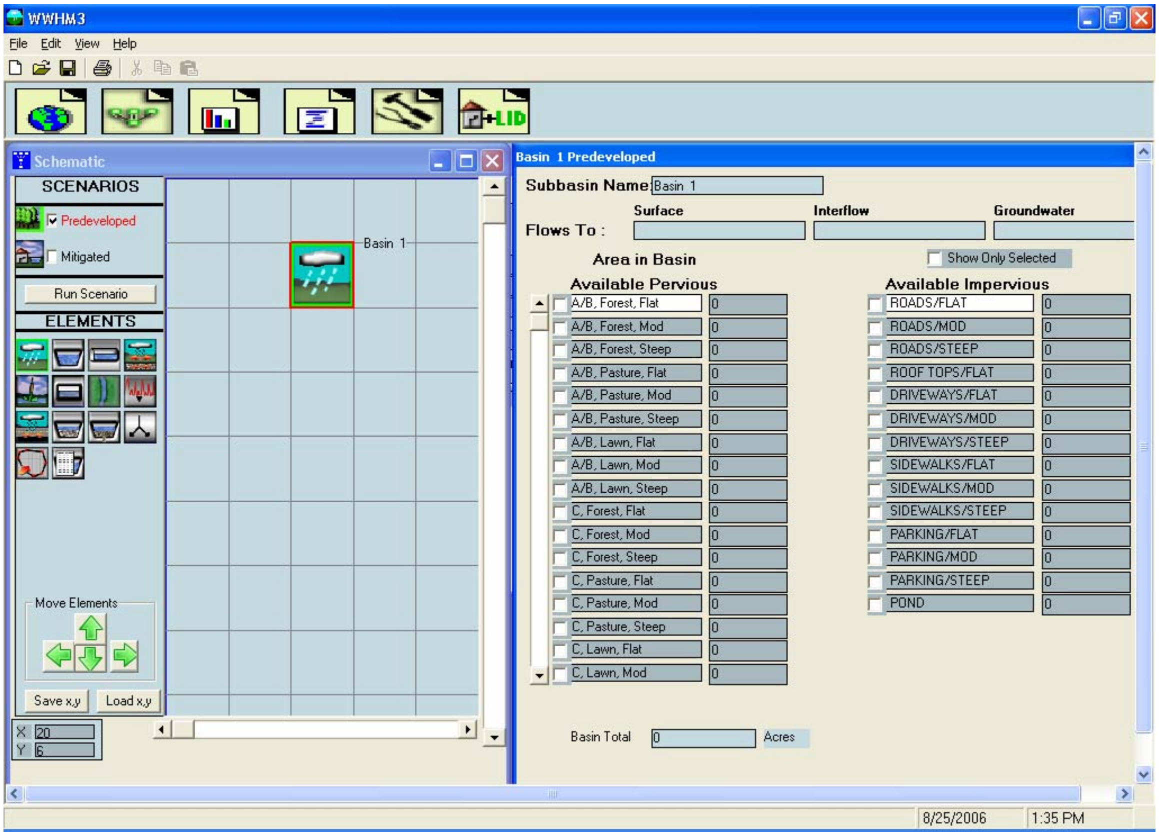
The project screen contains all of the information about the project site for the two land use scenarios: Predeveloped land use conditions and the Mitigated (developed) land use conditions. To change from one scenario to another check the box in front of the scenario name in the upper left corner of the screen.

Predeveloped is defined as the existing conditions prior to land use development. Runoff from the Predeveloped scenario is used as the target for the Mitigated scenario compliance. Unless there are special circumstances, the Department of Ecology requires that Predeveloped land use be Forest. However, the model will accept any land use for this scenario.

Mitigated is defined as the developed land use with mitigation measures (as selected by the user). Mitigated is used for sizing stormwater control and water quality facilities. The runoff from the Mitigated scenario is compared with the Predeveloped scenario runoff to determine compliance with Ecology standards.

Below the scenario boxes are the Elements (formerly called 'icons' in WWHM2). Each element represents a specific feature (basin, pond, etc.) and is described in more detail in the following section.

SCHEMATIC EDITOR



The project screen also contains the Schematic Editor. The Schematic Editor is the grid to the right of the elements. This grid is where each element is placed and linked together. The grid, using the scroll bars on the left and bottom, expands as large as needed to contain all of the elements for the project.

All movement on the grid must be from the top of the grid down.

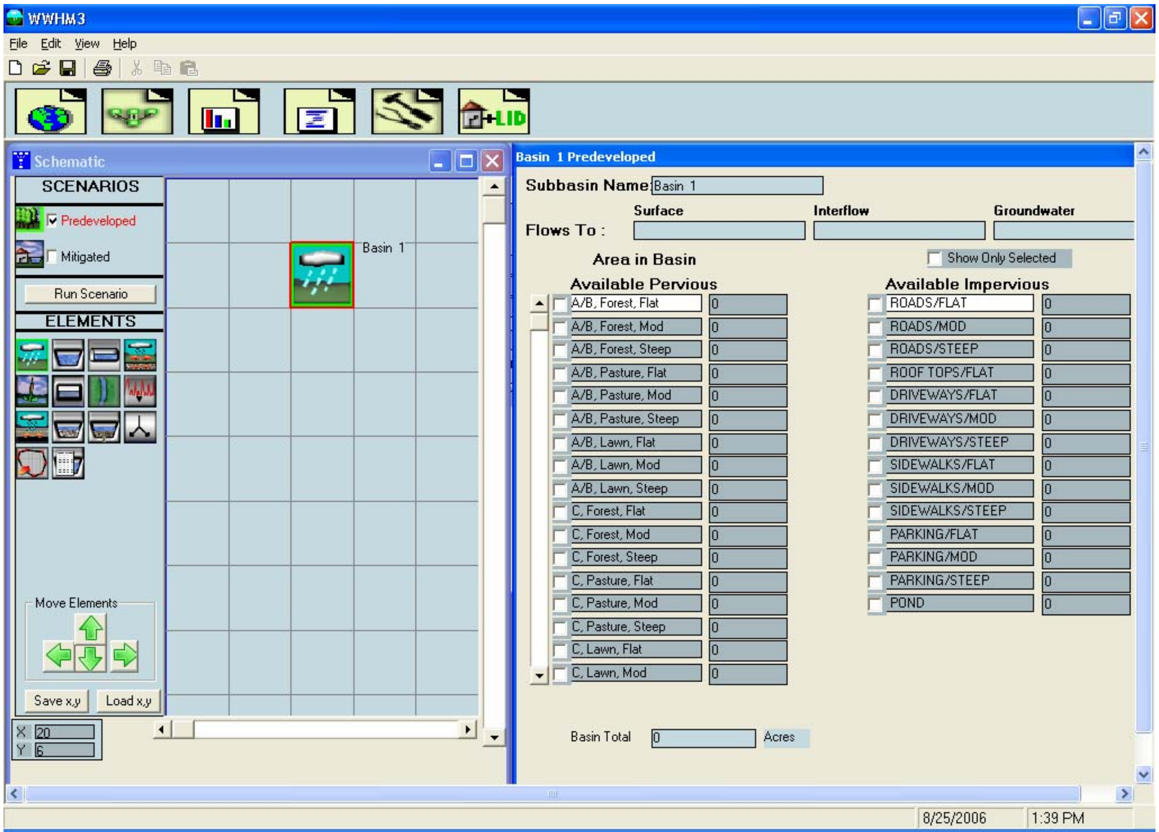
The space to the right of the grid will contain the appropriate element information.

To select and place an element on the grid, first left click on the specific element in the Elements menu and then left click on the selected grid square. The selected element will appear in the grid square. (DO NOT drag and drop the element, like in WWHM2.)

The entire grid can be moved up, down, left, or right using the Move Elements arrow buttons.

The gird coordinates from one project can be saved (Save x,y) and used for new projects (Load x,y).

BASIN



The Basin element represents a drainage area that can have any combination of soils, vegetation, and land uses. A basin produces three types of runoff: (1) surface runoff, (2) interflow, and (3) groundwater. The user can specify where each of these three types of runoff should be directed. The default setting is for the surface runoff and interflow to go to the stormwater facility; groundwater should not be connected unless there is observed base flow occurring in the drainage basin.

The user inputs the number of acres of appropriate basin land use information. Pervious land use information is in the form of soil, vegetation, and land slope. For example, "C, Forest, Flat" means SCS soil type C (till), forest vegetation, and flat (0-5%) land slope.

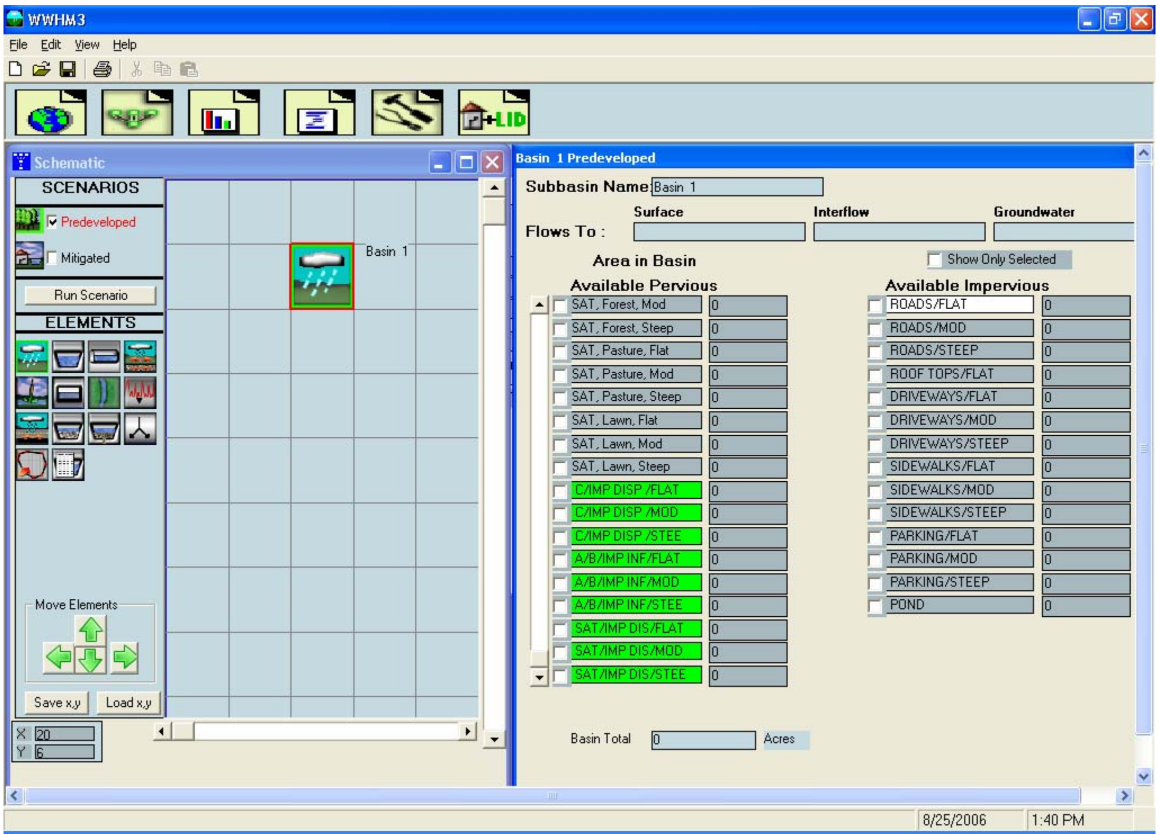
There are three basic soil types: A/B (outwash soils), C (till), and SAT (saturated/ wetland/hydric soils).

There are three basic vegetation categories: forest (second growth Douglas Fir), pasture (non-forested natural areas/scrub/shrub rural vegetation), and lawn (sod lawn/grass/ landscaped urban vegetation).

There are also three land slope categories: flat (0-5%), moderate (5-15%), and steep (>15%).

Impervious areas are divided into five types with three different slopes. The four types are: roads, roofs, driveways, sidewalks, and parking. The slope categories are the same as for the pervious land use (flat, moderate, steep). Pond area is also listed as an impervious area.

Runoff credits are included in the nine pervious land categories at the bottom of the Available Pervious list (see below).



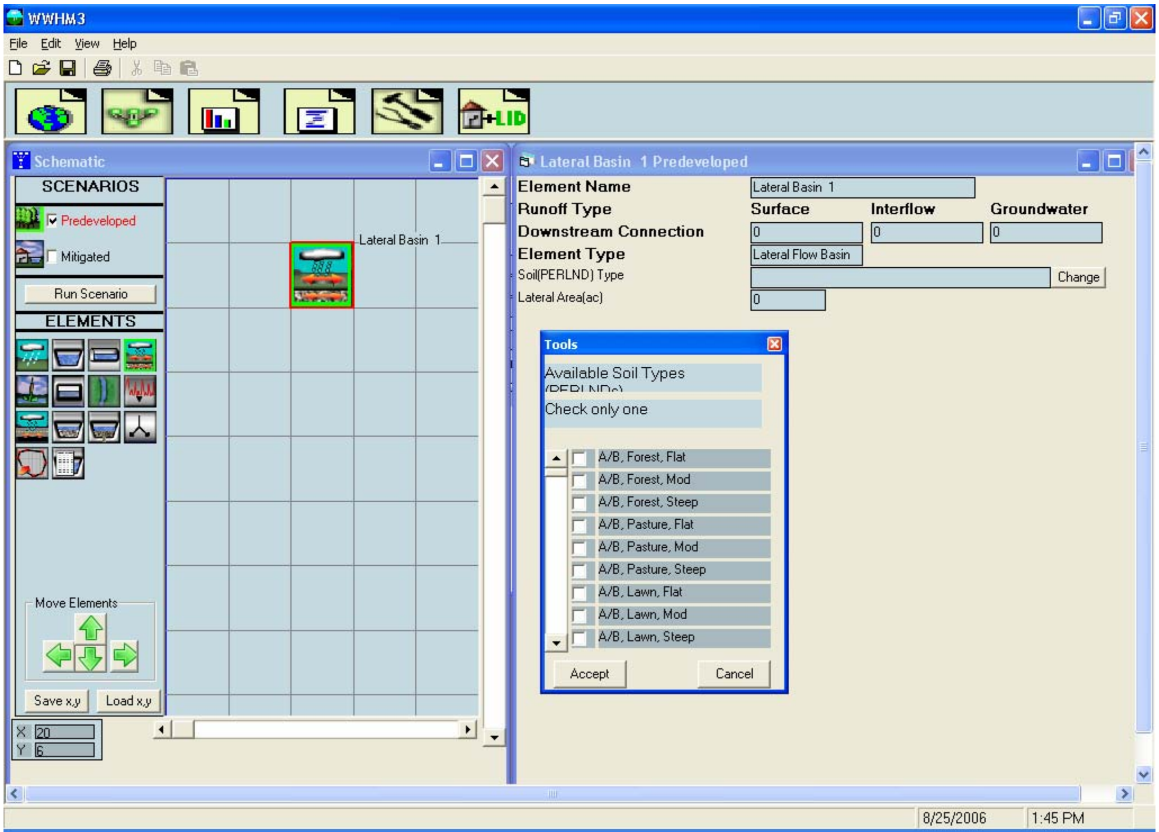
These eight land uses are:
(1) C/IMP DISP/FLAT = Dispersal of impervious area runoff on C soil with flat slope.
(2) C/IMP DISP/MOD = Dispersal of impervious area runoff on C soil with moderate slope.
(3) C/IMP DISP/STEEP = Dispersal of impervious area runoff on C soil with steep slope.
(4) A/B/IMP INF/FLAT = Infiltration of impervious area runoff on A/B soil with flat slope.
(5) A/B/IMP INF/MOD = Infiltration of impervious area runoff on A/B soil with moderate slope.
(6) A/B/IMP INF/STEEP = Infiltration of impervious area runoff on A/B soil with steep slope.
(7) SAT/IMP DISP/FLAT = Dispersal of impervious area runoff on saturated soil with flat slope.

(8) SAT/IMP DISP/MOD = Dispersal of impervious area runoff on saturated soil with moderate slope.
(9) SAT/IMP DISP/STEEP = Dispersal of impervious area runoff on saturated soil with steep slope.

The standard residential option (WWHM2) is not explicitly included in WWHM3. The user can still use the standard residential default values by manually computing and adding the appropriate areas to the basin land use information. The standard residential default values are:

- 3200 square feet (0.073 acres) of roof per residential lot
- 1000 square feet (0.023 acres) of driveway per residential lot
- the remainder of the residential lot is considered to be lawn.

LATERAL BASIN (Pervious)



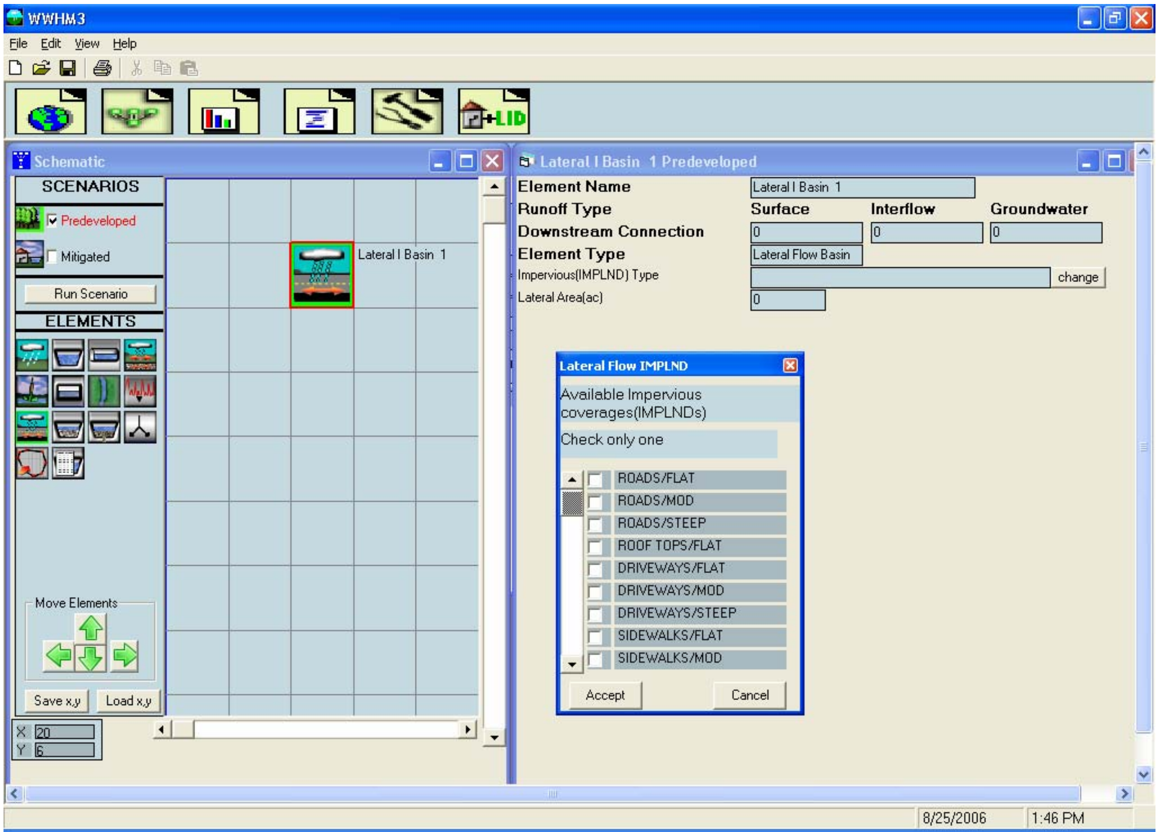
The pervious lateral basin is similar to the standard basin except that the runoff from the lateral basin goes to another adjacent lateral basin (impervious or pervious) rather than directly to a conveyance system or stormwater facility. By definition, the pervious lateral basin contains only a single pervious land type. Impervious area is handled separately with the impervious lateral basin (Lateral I Basin).

The user selects the pervious lateral basin land type by checking the appropriate box on the Available Soil Types Tools screen. This information is automatically placed in the Soil (PERLND) Type box above. Once entered, the land type can be changed by clicking on the Change button on the right.

The user enters the number of acres represented by the lateral basin land type.

If the lateral basin contains two or more pervious land use types then the user should create a separate lateral basin for each.

LATERAL I BASIN (Impervious)



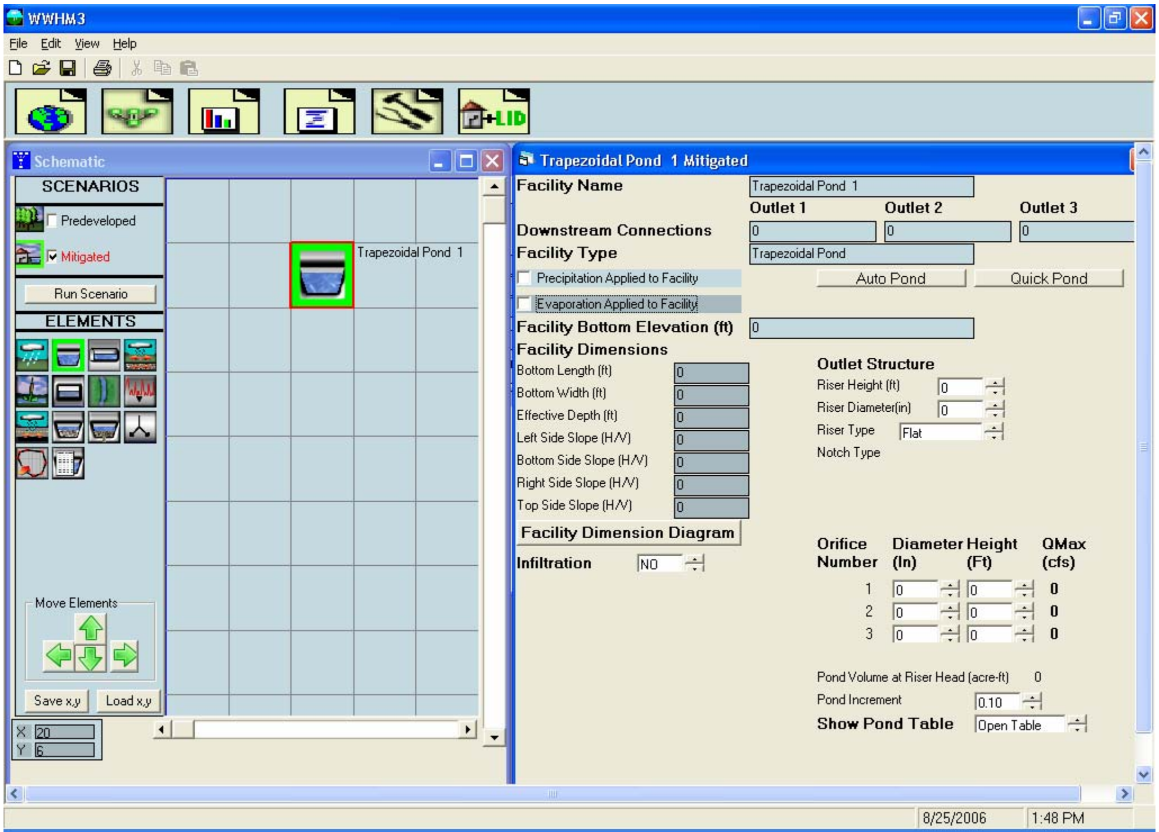
The impervious lateral basin is similar to the standard basin except that the surface runoff from the lateral impervious basin goes to another adjacent lateral basin (impervious or pervious) rather than directly to a conveyance system or stormwater facility. By definition, the impervious lateral basin contains only impervious land types. Pervious area is handled separately with the pervious lateral basin (Lateral Basin).

The user selects the impervious lateral basin land type by checking the appropriate box on the Available Impervious Coverages screen. This information is automatically placed in the Impervious (IMPLND) Type box above. Once entered, the land type can be changed by clicking on the Change button on the right.

The user enters the number of acres represented by the lateral impervious basin land type.

If the lateral impervious basin contains two or more impervious land use types then the user should create a separate lateral I basin for each.

TRAPEZOIDAL POND



In WWHM3 there is an individual pond element for each type of pond and stormwater control facility. The pond element shown above is for a trapezoidal pond. This is the most common type of stormwater pond.

A trapezoidal pond has dimensions (bottom length and width, depth, and side slopes) and an outlet structure consisting of a riser and one or more orifices to control the release of stormwater from the pond. A trapezoidal pond includes the option to infiltrate runoff, if the soils are appropriate and there is sufficient depth to the underlying groundwater table.

The user has the option to specify that different outlets be directed to different downstream destinations, although usually all of the outlets go to a single downstream location.

AutoPond will automatically size a trapezoidal pond to meet Ecology flow control standards. QuickPond will instantly create a pond without checking it for compliancy with Ecology standards.

The user can change the default name “Trapezoidal Pond 1” to another more appropriate name, if desired.

Precipitation and evaporation can be applied to the pond. The default standard setting is not to apply precipitation and evaporation, but to treat the pond surface area as an impervious surface.

The pond bottom elevation can be set to an elevation other than zero if the user wants to actual elevations. All pond stage values are relative to the bottom elevation. Negative bottom elevations are not allowed.

The pond effective depth is the pond height (including freeboard) above the pond bottom. It is not the actual elevation of the top of the pond.

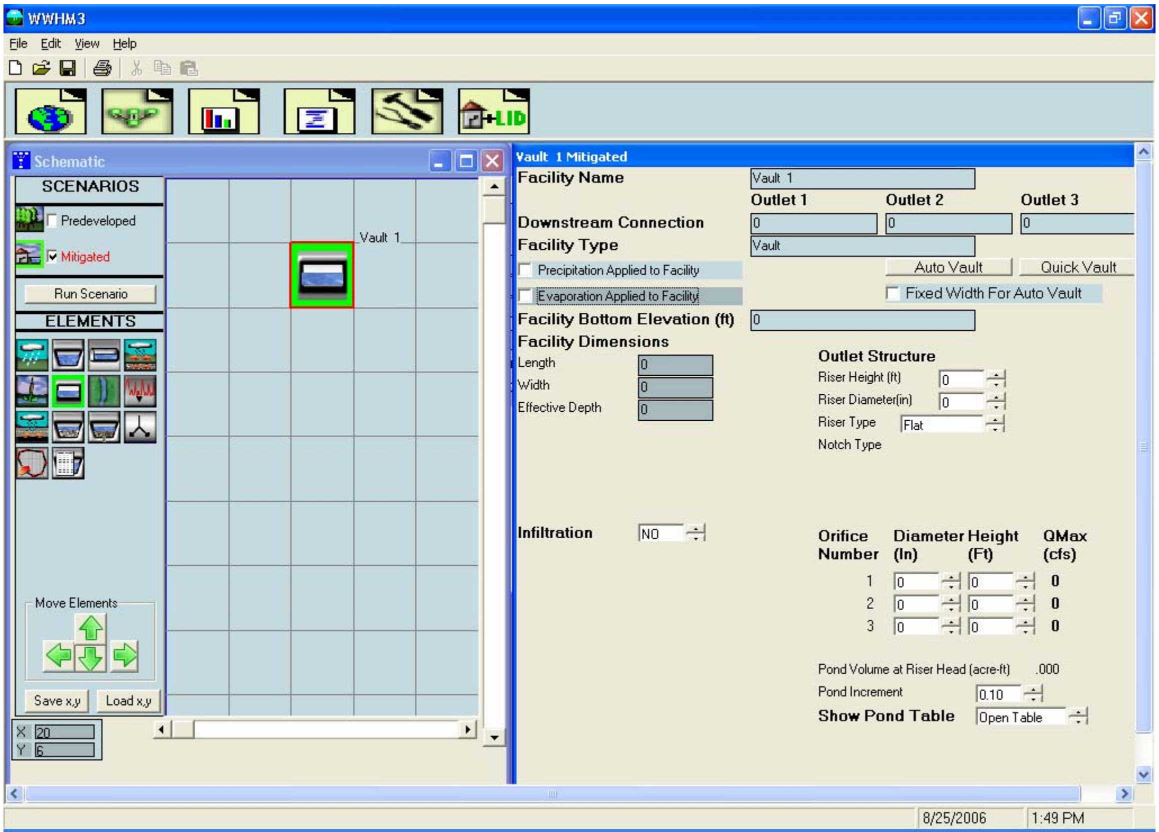
Pond side slopes are in terms of horizontal distance over vertical. A standard 3:1 (H/V) side slope would be given a value of 3. A vertical side slope has a value of 0.

The pond bottom is assumed to be flat.

The pond outlet structure consists of a riser and zero to three orifices. The riser has a height (typically one foot less than the effective depth) and a diameter. The riser can have either a flat top or a weir notch cut into the side of the top of the riser. The notch can be either rectangular, V-shaped, or a Sutro weir. More information on the riser weir shapes and orifices is provided later in this manual.

After the pond is given dimensions and outlet information the user can view the resulting stage-storage-discharge table by clicking on the “Open Table” arrow in the lower right corner of the pond information screen. This table hydraulically defines the pond’s characteristics.

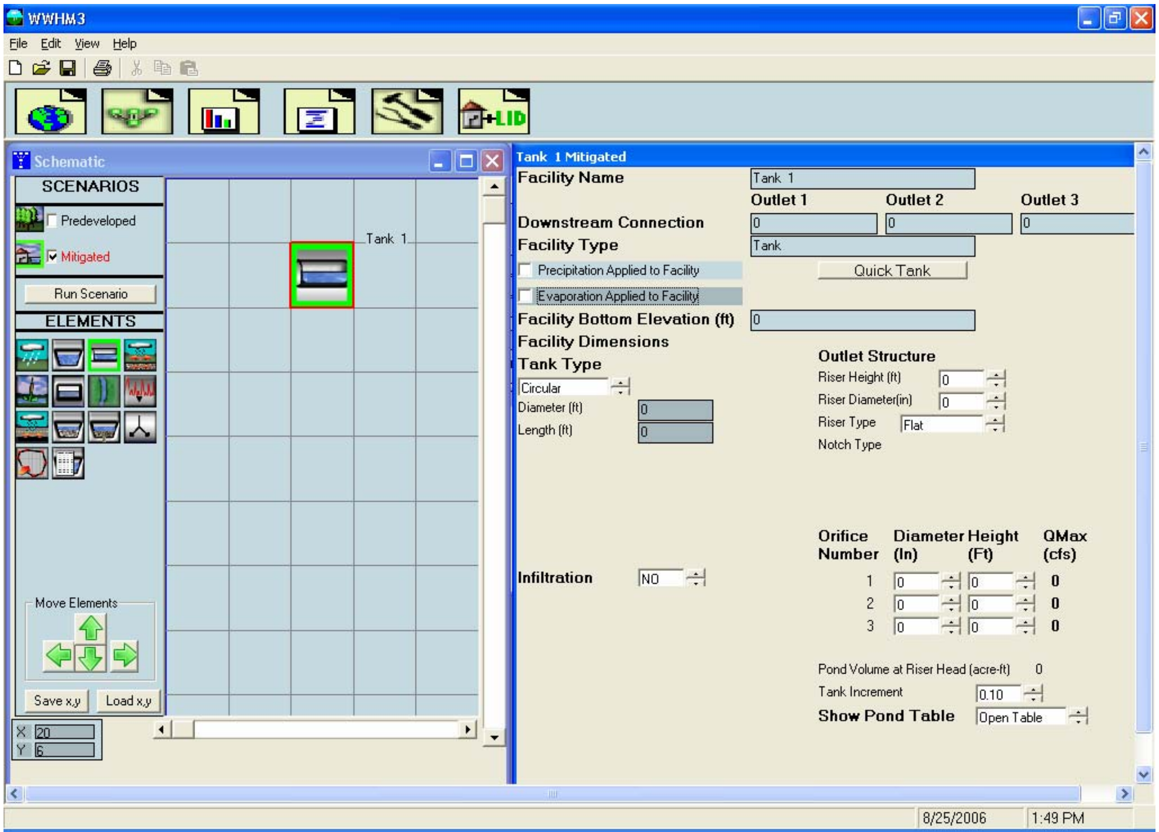
VAULT



The storage vault has all of the same characteristics of the trapezoidal pond, except that the user does not specify the side slopes (by definition they are zero).

AutoVault and QuickVault work the same way as AutoPond and QuickPond.

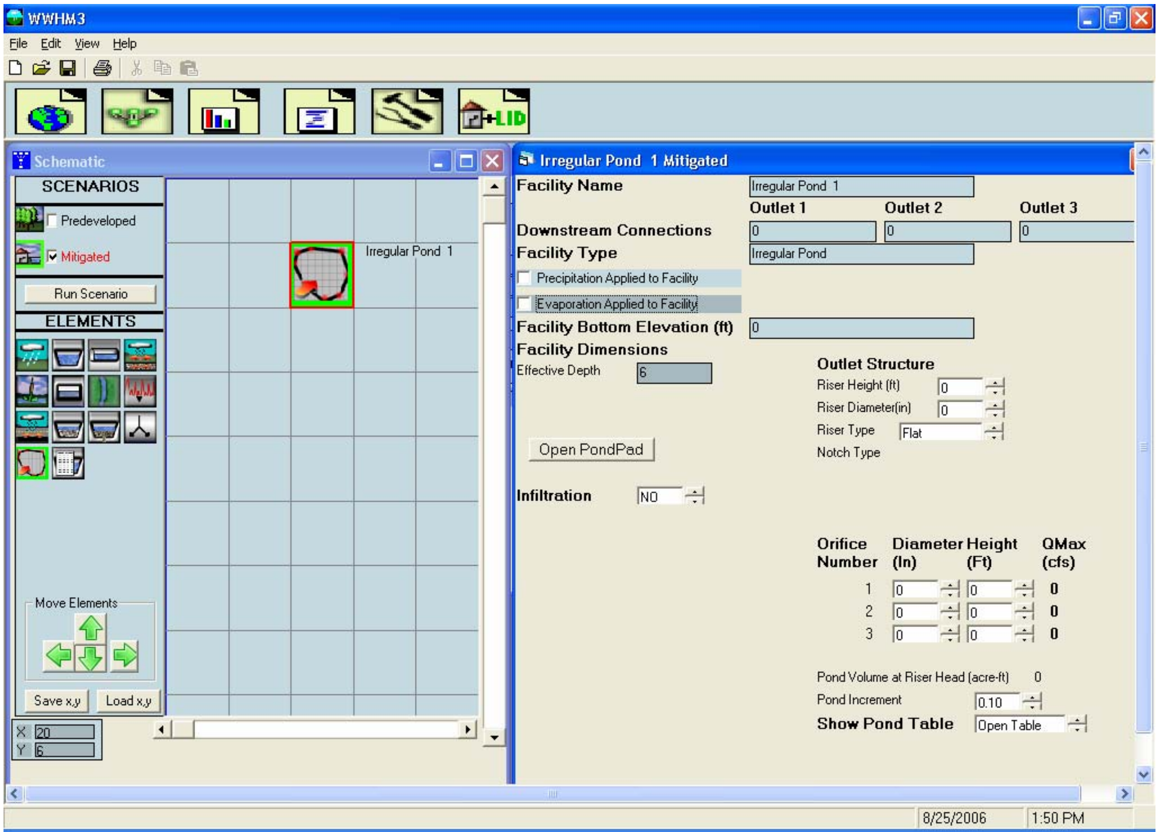
TANK



A storage tank is a cylinder placed on its side. The user specifies the tank's diameter and length.

There is no AutoTank (automatic tank sizing routine). The user must manually size the tank to meet Ecology's standards. There is a QuickTank option that creates a tank, but does not check for compliance with Ecology's standards.

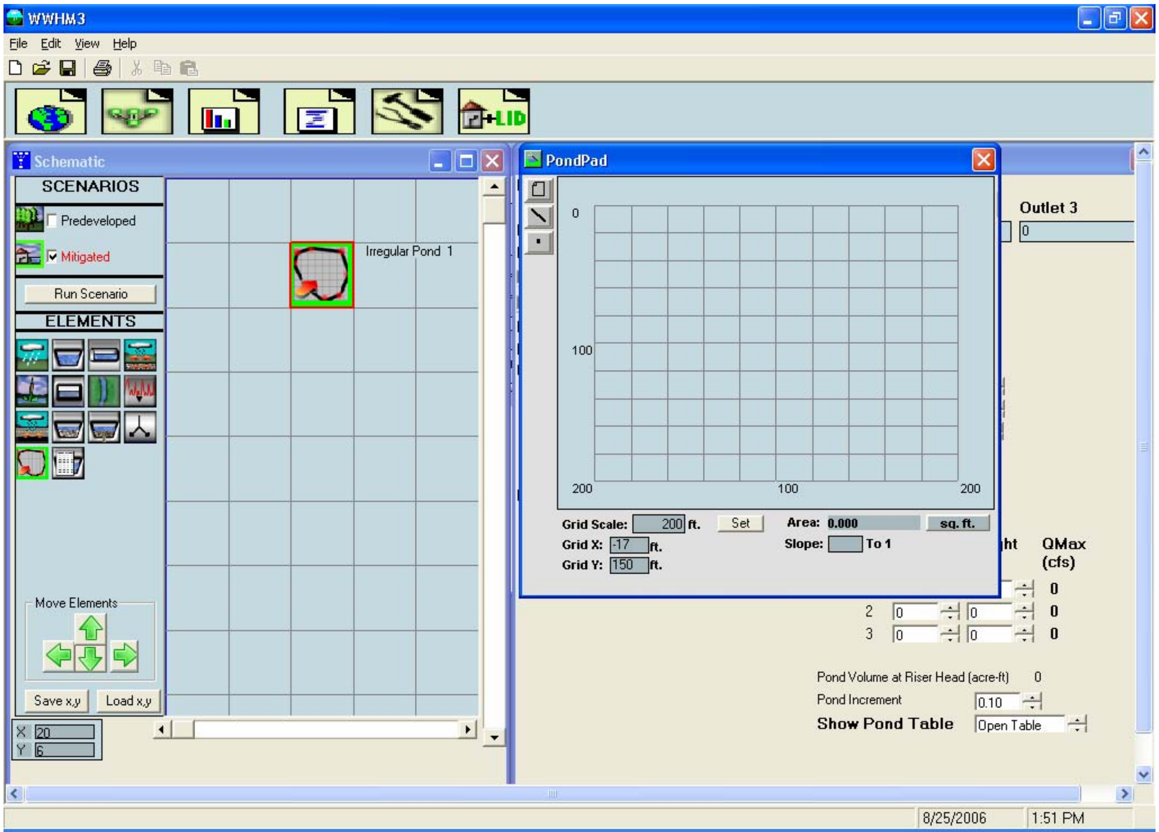
IRREGULAR POND



An irregular pond is any pond with a shape that differs from the rectangular top of a trapezoidal pond. An irregular pond has all of the same characteristics of a trapezoidal pond, but its shape must be defined by the user.

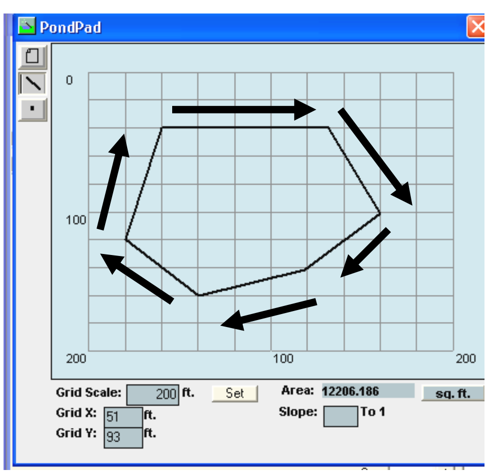
To create the shape of an irregular pond the user clicks on the “Open PondPad” button. This allows the user to access the PondPad interface (see below).

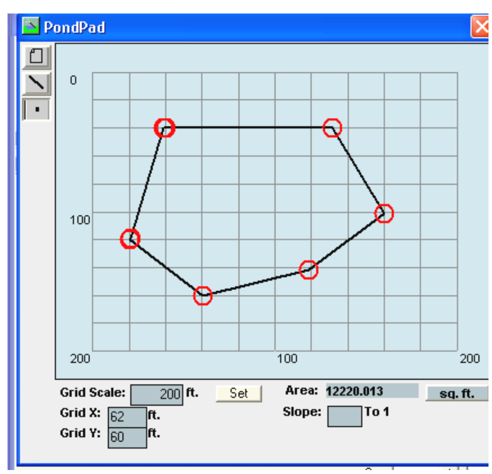
PondPad Interface



The PondPad interface is a grid on which the user can specify the outline of the top of the pond and the pond's side slopes.

The user selects the line button (second from the top on the upper left corner of the PondPad screen). Once the line button is turned on the user moves the mouse over the grid to locate the pond's corner points. The user does this in a clockwise direction to outline the pond's top perimeter. The user can select individual points by clicking on the point button immediately below the line button. Once selected, any individual point can be moved or repositioned.





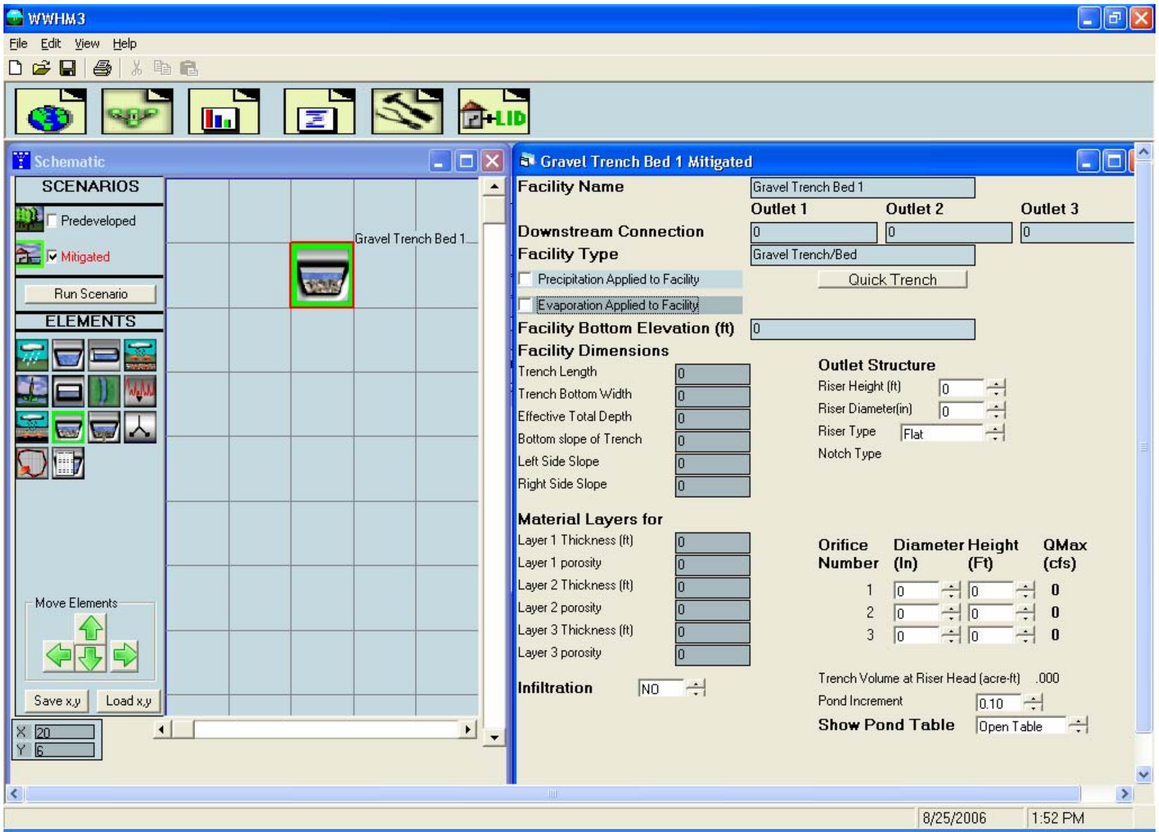
The default side slope value is 3 (3:1). The side slopes can be individually changed by right clicking on the specific side (which changes the line color from black to red) and then entering the individual side slope value in the slope text box.

The grid scale can be changed by entering a new value in the grid scale box. The default value is 200 feet.

PondPad Controls and Numbers

Clear:	The Clear button clears all of the lines on the grid.
Line:	The Line button allows the user to draw new lines with the mouse.
Point:	The Point button allows the user to move individual points to alter the pond shape and size.
Sq Ft:	Converts the computed pond area from square feet to acres and back.
Grid Scale:	Changes the length of a grid line. Default grid scale is 200 feet.
Grid X:	Horizontal location of the mouse pointer on the grid (0 is the upper left corner).
Grid Y:	Vertical location of the mouse pointer on the grid (0 is the upper left corner)
Area:	Top area of the pond (either in square feet or acres).
Slope:	Side slope of the selected line (side of the pond).

GRAVEL TRENCH BED



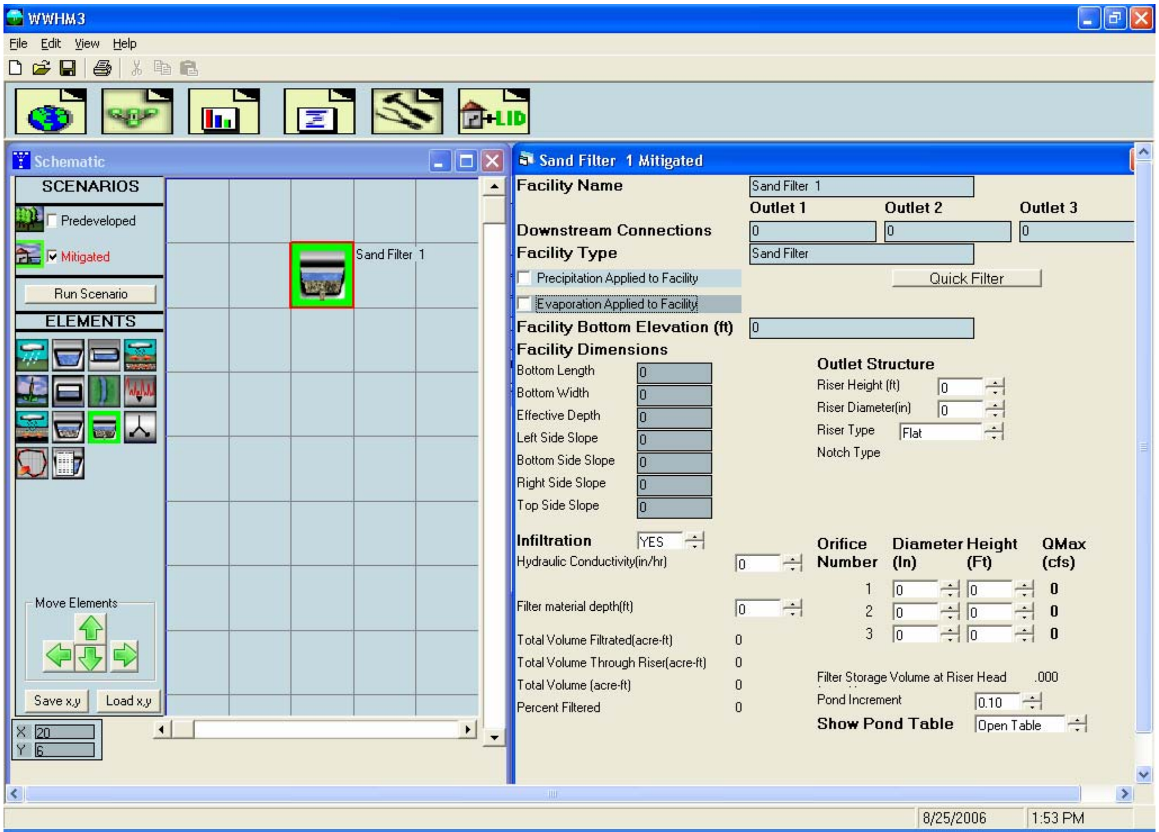
The gravel trench bed is a new feature in WWHM3. It is used to spread and infiltrate runoff, but also can have one or more surface outlets represented by an outlet structure with a riser and multiple orifices.

The user specifies the trench length, bottom width, total depth, bottom slope, and left and right side slopes.

The material layers represent the amended soils and their design characteristics (thickness and porosity). These are the soil layers added to the gravel trench bed to filter the runoff prior to dispersal.

QuickTrench will instantly create a gravel trench bed with default values without checking it for compliancy with Ecology standards.

SAND FILTER



The sand filter is a water quality facility. It does not infiltrate runoff, but is used to filter runoff through a medium and sent it downstream. It can also have one or more surface outlets represented by an outlet structure with a riser and multiple orifices.

The user must specify the facility dimensions (bottom length and width, effective depth, and side slopes. The hydraulic conductivity of the sand filter and the filter material depth are also needed to size the sand filter (default values are 1.0 and 1.5, respectively). The goal of the sand filter is meet the Ecology treatment standard of filtering at least 91% of the total runoff volume.

The filter discharge is calculated using the equation Q = K*I*A, where Q is the discharge in cubic feet per second (cfs). K equals the hydraulic conductivity (inches per hour). For sand filters K = 1.0 in/hr. Sand is the default medium. If another filtration material is used then the design engineer should enter the appropriate K value supported by documentation and approval by the reviewing authority.

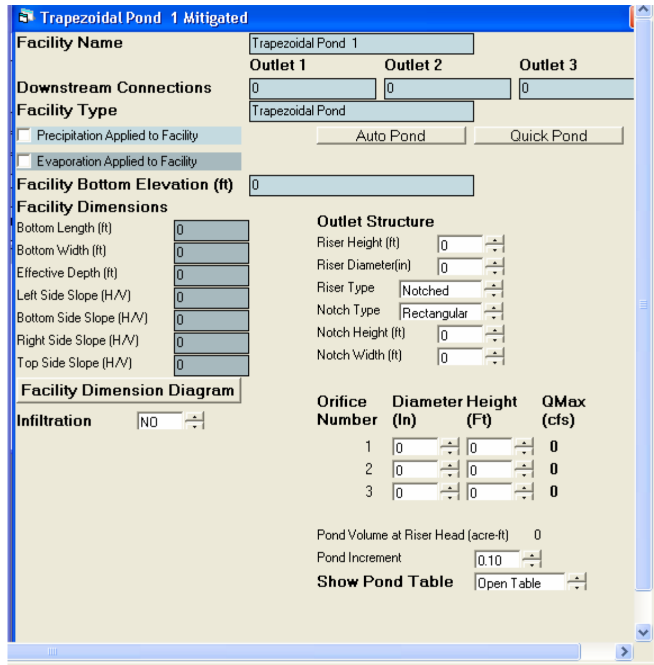
Design of a sand filter requires input of facility dimensions and outlet structure characteristics, running the sand filter scenario, and then checking the volume calculations to see if the Percent Filtered equals or exceeds 91.0%. If the value is less than 91% then the user should increase the size of the sand filter dimensions and/or change the outlet structure.

RISER/WEIR

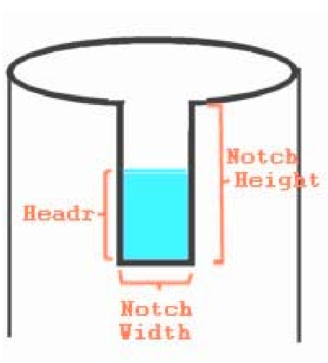
The trapezoidal pond, vault, tank, irregular pond, gravel trench bed, and sand filter all use a riser for the outlet structure to control discharge from the facility.

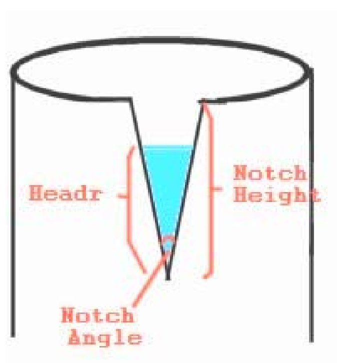
The riser is a vertical pipe with a height above pond bottom (typically one foot less than the effective depth). The user specifies the riser height and diameter.

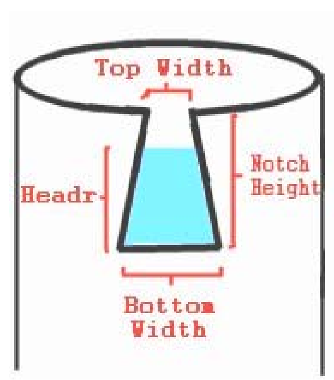
The riser can have up to three round orifices. The bottom orifice is usually located at the bottom of the pond and/or above any dead storage in the facility. The user can set the diameter and height of each orifice. The model will automatically calculate the maximum orifice discharge value, QMax (cfs), if the pond dimensions have already been defined.



The user specifies the riser type as either flat or notched. The weir notch can be either rectangular, V-notch, or a Sutro weir. The shape of each type of weir is shown below.







Rectangular Notch V-Notch Sutro

By selecting the appropriate notch type the user is then given the option to enter the appropriate notch type dimensions.

Riser and orifice equations used in WWHM3 are provided below.

Headr = the water height over the notch/orifice bottom.
q = discharge

Riser Head Discharge:

Head = water level above riser
q = 9.739 * Riser Diameter * Head ^ 1.5

Orifice Equation:
q = 3.782 * (Orifice Diameter) ^ 2 * SQRT(Headr)

Rectangular Notch:
b = NotchWidth *- (1- 0.2 * Headr)
where b >= 0.8
q = 3.33 * b * Headr ^ 1.5

Sutro:
Wh = Top Width + {(Bottom Width- Top Width)/Notch Height }* Headr
Wd = Bottom Width - Wh (the difference between the bottom and top widths)

Q1 = (rectangular notch q where Notch Width = Wh)
Q2 = (rectangular notch q where Notch Width = Wd)

q = Q1 + Q2 / 2

V-Notch:
Notch Bottom = height from bottom of riser to bottom of notch
Theta = Notch Angle

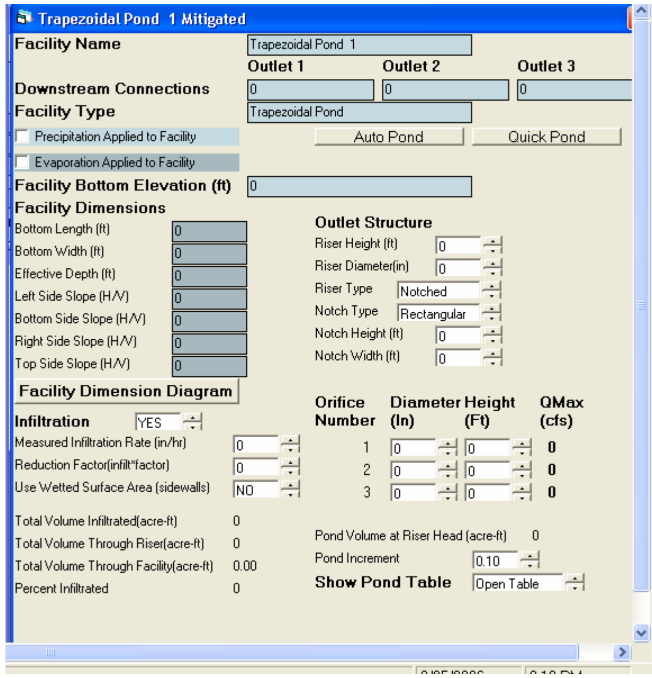
a = 2.664261 - 0.0018641 * Theta + 0.00005761 * Theta ^2
b = -0.48875 + 0.003843 * Theta - 0.000092124 * Theta ^2
c = 0.3392 - 0.0024318 * Theta + 0.00004715 * Theta ^2

YoverH = Headr / (NotchBottom + Headr)
Coef = a + b * Headr + c * Headr ^2

q = (Coef * Tan(Theta / 2)) * (Headr ^ (5 / 2))

INFILTRATION

Infiltration of stormwater runoff is a recommended solution if certain conditions are met. These conditions include: a soils report, testing, groundwater protection, pre-settling, and appropriate construction techniques (see Ecology's Stormwater Management Manual for Western Washington for details).



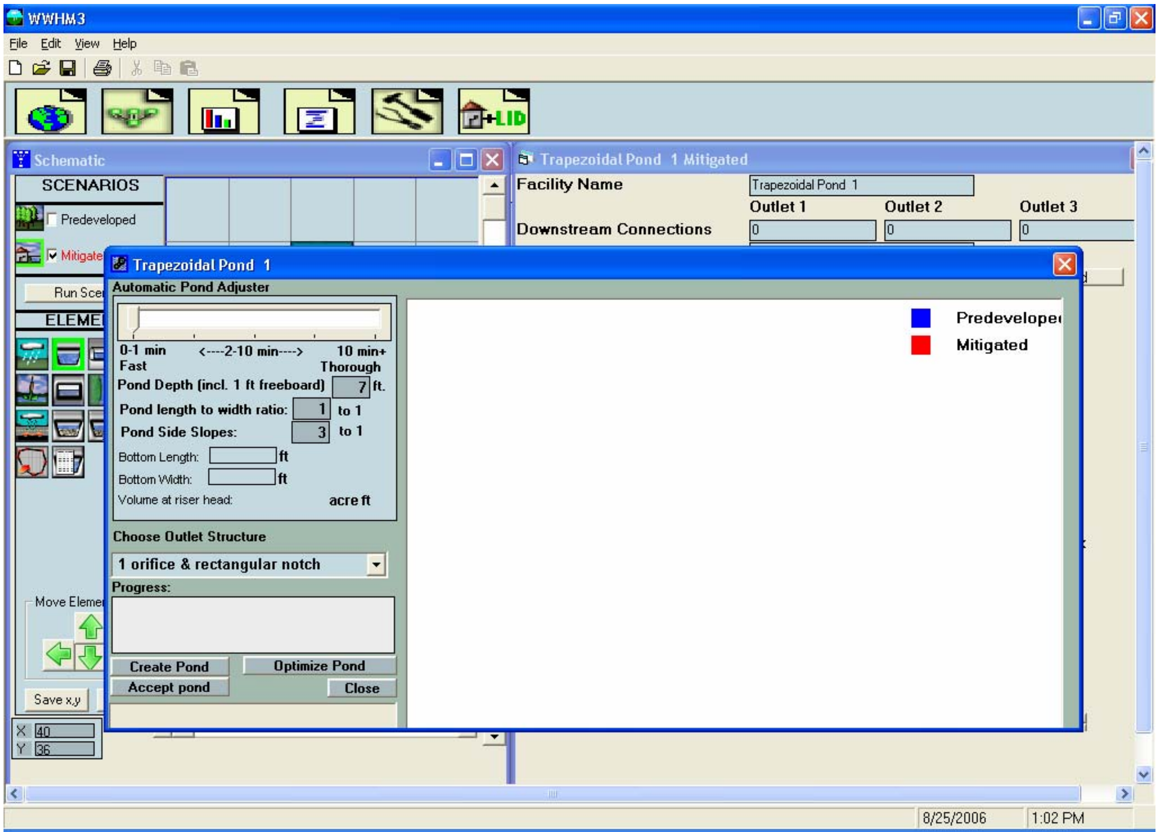
The user clicks on the Infiltration option arrow to change infiltration from NO to YES. This activates the infiltration input options: measured infiltration rate, infiltration reduction factor, and whether or not to allow infiltration through the wetted side slopes/walls.

The infiltration reduction factor is a multiplier for the measured infiltration rate and should be less than one. It is the same as the inverse of a safety factor. For example, a safety factor of 2 is equal to a reduction factor of 0.5.

Infiltration occurs only through the bottom of the facility if the wetted surface area option is turned off. Otherwise the entire wetted surface area is used for infiltration.

After the model is run and flow is routed through the infiltration facility the total volume infiltrated, total volume through the riser, total volume through the facility, and percent infiltrated are reported on the screen. If the percent infiltrated is 100% then there is no surface discharge from the facility. The percent infiltrated can be less than 100% as long as the surface discharge does not exceed Ecology's flow control standards.

AUTOPOND



AutoPond automatically creates a pond size and designs the outlet structure to meet Ecology's flow duration criteria. The user can either create a pond from scratch or optimize an existing pond design.

AutoPond requires that the Predeveloped and Mitigated basins be defined prior to using AutoPond. Clicking on the AutoPond button brings up the AutoPond window and the associated AutoPond controls.

AutoPond controls:

Automatic Pond Adjuster: The slider at the top of the AutoPond window allows the user to decide how thoroughly the pond will be designed for efficiency. The lowest setting (0-1 min) at the left constructs an initial pond with checking it for Ecology's flow duration criteria. The second setting to the right creates and sizes a pond to pass Ecology's flow duration criteria; however, the pond is not necessarily optimized. The higher settings increase the amount of optimization. The highest setting (farthest left) will size the most efficient (smallest) pond, but will result in longer computational time.

Pond Depth: Pond depth is the total depth of the pond and should include at least one foot of freeboard (above the riser). The pond's original depth will be used when optimizing an existing pond; changing the value in the Pond Depth text box will override any previous set depth value. The default depth is 7 feet.

Pond Length to Width Ratio: This bottom length to width ratio will be maintained regardless of the pond size or orientation. The default ratio value is 1.0

Pond Side Slopes: AutoPond assumes that all of the pond's sides have the same side slope. The side slope is defined as the horizontal distance divided by the vertical. A typical side slope is 3 (3 feet horizontal to every 1 foot vertical). The default side slope value is 3.

Choose Outlet Structure: The user has the choice of either 1 orifice and rectangular notch or 3 orifices. If the user wants to select another outlet structure option then the pond must be manually sized.

Create Pond: This button creates a pond when the user does not input any pond dimensions or outlet structure information. Any previously input pond information will be deleted.

Optimize Pond: This button optimizes an existing pond. It cannot be used if the user has not already created a pond.

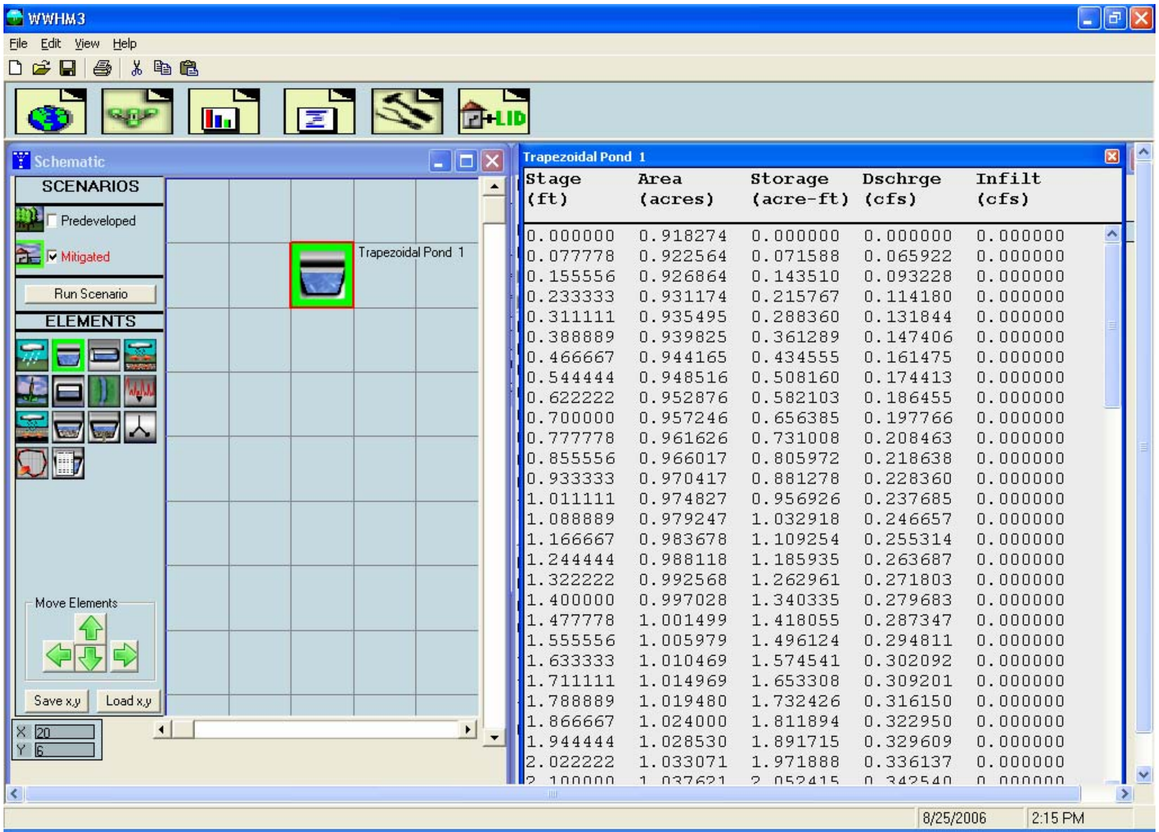
Accept Pond: This button will stop the AutoPond routine at the last pond size and discharge characteristics that produce a pond that passes Ecology's flow duration criteria. AutoPond will not stop immediately if the flow duration criteria has not yet been met.

The bottom length and width and volume at riser head will be computed by AutoPond; they cannot be input by the user.

AutoVault operates the same way as AutoPond.

There are some situations where AutoPond (or AutoVault) will not work. These situations occur when complex routing conditions upstream of the pond make it difficult or impossible for AutoPond to determine which land use will be contributing runoff to the pond. For these situations the pond will have to be manually sized.

STAGE-STORAGE-DISCHARGE TABLE

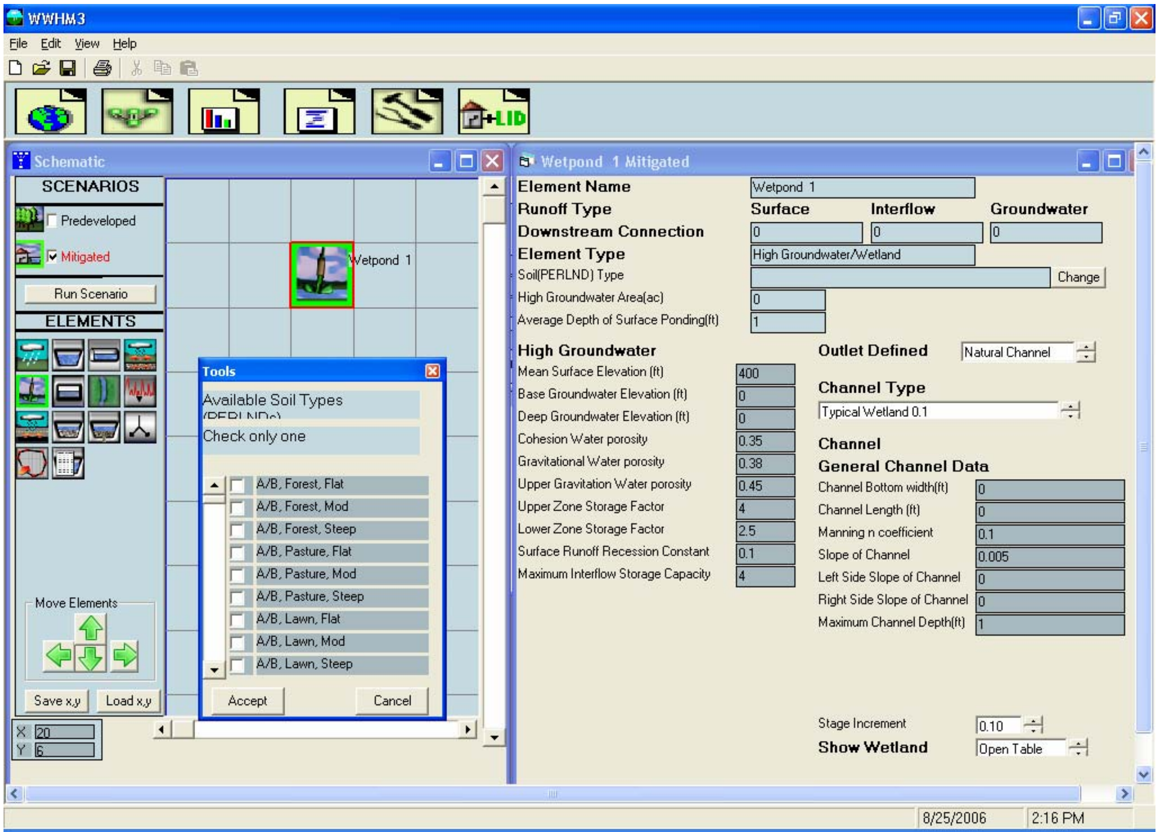


The stage-storage-discharge table hydraulically represents any facility that requires stormwater routing. The table is automatically generated by WWHM3 when the user inputs storage facility dimensions and outlet structure information. The WWHM3 generates 100 lines of stage, surface area, storage, surface discharge, and infiltration values starting at a stage value of zero (facility bottom height) and increasing in equal increments to the maximum stage value (facility effective depth).

When the user or WWHM3 changes a facility dimension (for example, bottom length) or an orifice diameter or height the model immediately recalculates the stage-storage-discharge table.

The user can input to WWHM3 a stage-storage-discharge table created elsewhere. A separate element, SSD Table, is required. See the SSD Table description below for more information on how to load such a table to the WWHM3 program.

HIGH GROUNDWATER/WETLAND



The High Groundwater/Wetland element is a complex element that should only be used in special applications by advanced WWHM3 users. The purpose of the high groundwater/wetland element is to model hydrologic conditions where high groundwater rises to the surface (or near the surface) and reduces the ability of water to infiltrate into the soil.

The element can be used to represent wetland conditions with surface ponding where the discharge from the wetland is via a surface release. The user is given the choice of using either a natural channel, berm/weir, or control structure to determine the release characteristics.

The element provides default values for some of the parameters, especially as they relate to high groundwater. The user should be fully familiar with these parameters and the appropriate values for their site prior to attempting to use this element. The high groundwater parameter definitions are shown below.

Cohension water porosity: soil pore space in micropores.

Gravitational water porosity: soil pore space in macropores in the lower and groundwater layers of the soil column.

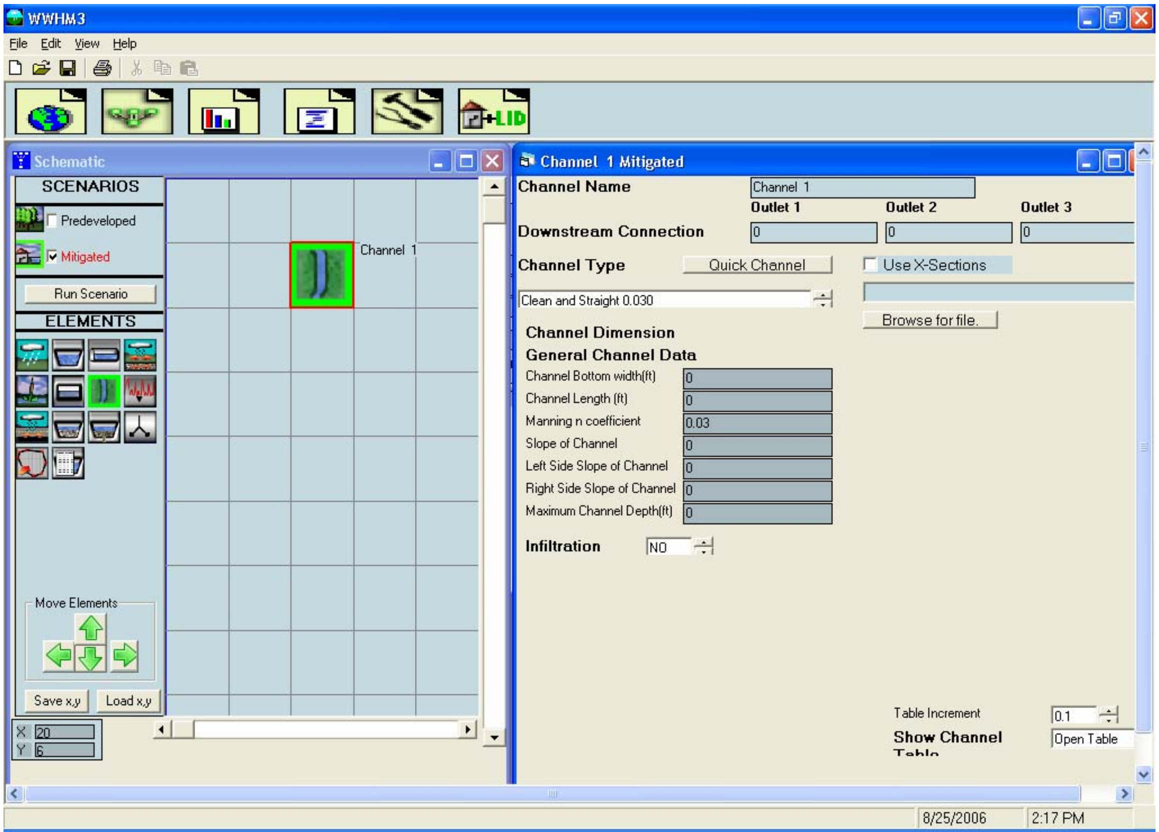
Upper gravitation water porosity: soil pore space in macropores in the upper layer of the soil column.

Upper zone storage factor: portion of the water stored in macropores in the upper soil layer which will not surface discharge, but will percolate, evaporate or transpire.

Lower zone storage factor: portion of the water stored in micropores in the lower soil layer which will not gravity drain, but will evaporate or transpire.

Additional documentation is available in “WWHM3 Description of HSPF High Groundwater Parameters” available from the Washington State Department of Ecology.

CHANNEL



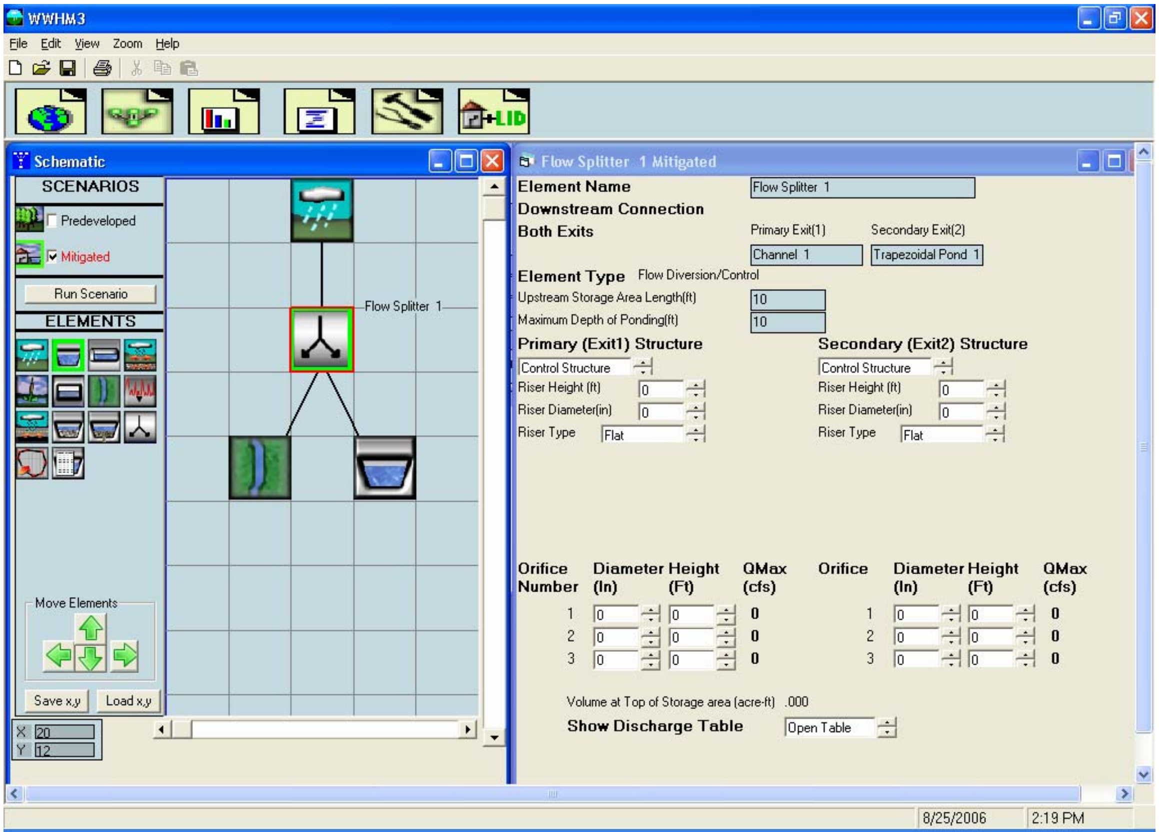
The Channel element is a new feature in WWHM3. Channel allows the user to route runoff from a basin or facility through an open channel to a downstream destination.

The channel cross section is represented by a trapezoid and is used with Manning's equation to calculate discharge from the channel. If a trapezoid does not accurately represent the cross section then the user should represent the channel with an independently calculated SSD Table element or use the Use X-Sections option.

The user inputs channel bottom width, channel length, channel bottom slope, channel left and right side slopes, maximum channel depth, and the channel's roughness coefficient (Manning's n value). The user can select channel type and associated Manning's n from a table list directly above the Channel Dimension information or directly input the channel's Manning's n value.

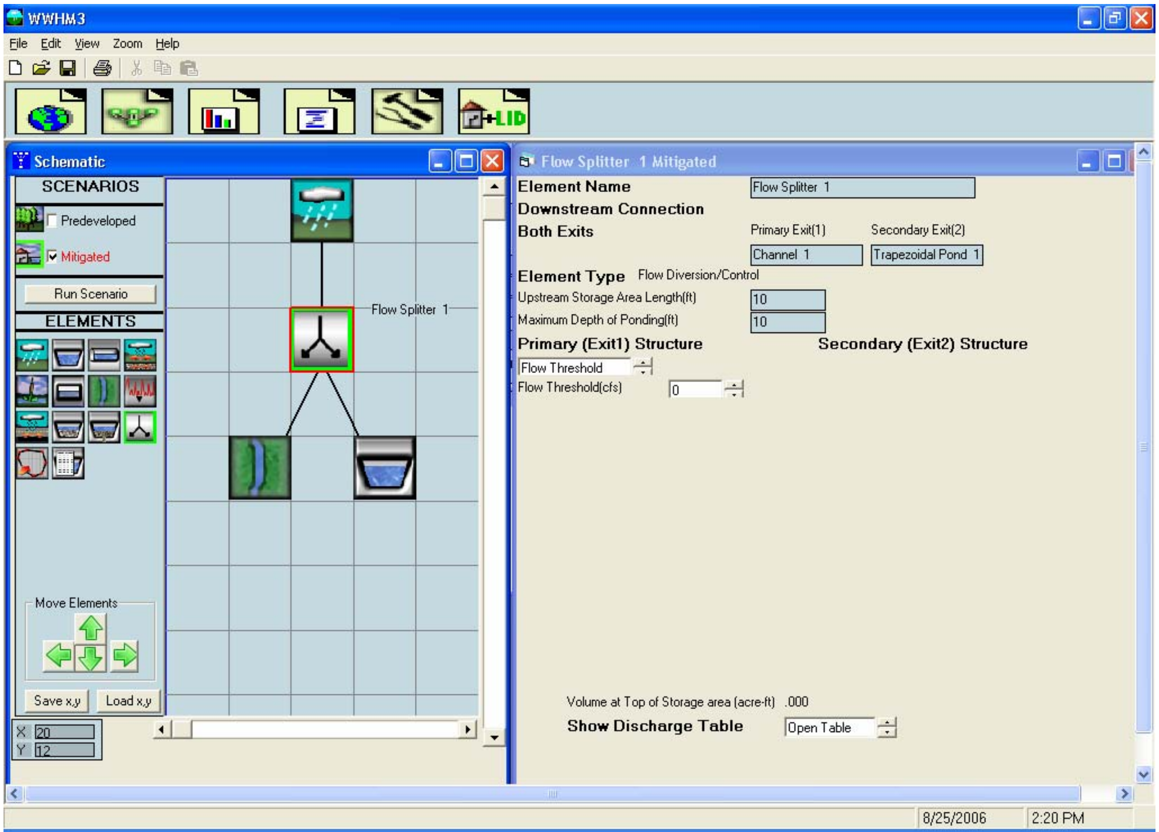
The channel is used to represent a natural or artificial open channel through which water is routed. It can be used to connect a basin to a pond or a pond to a pond or multiple channels can linked together.

FLOW SPLITTER



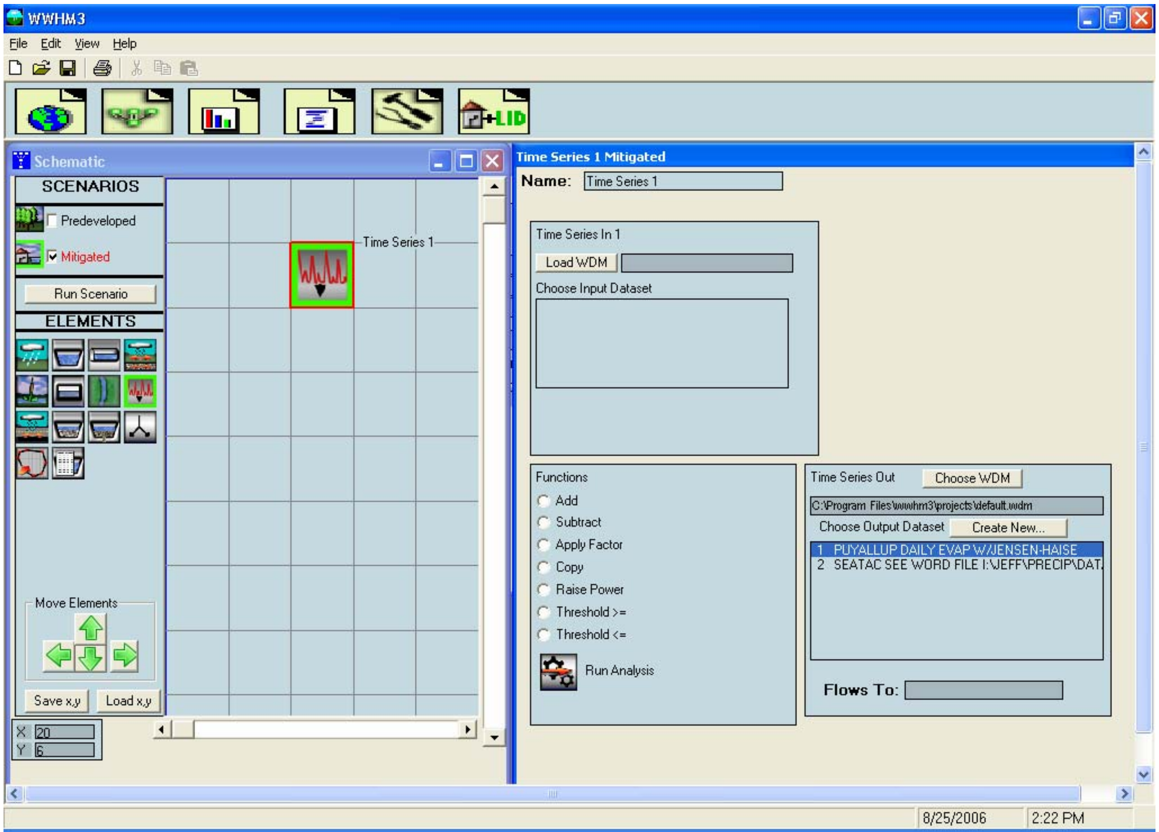
The flow splitter divides the runoff and sends it to two difference destinations. The splitter has a primary exit (exit 1) and a secondary exit (exit 2). The user defines how the flow is split between these two exits.

The user can define a flow control structure with a riser and one to three orifices for each exit. The flow control structure works the same way as the pond outlet structure, with the user setting the riser height and diameter, the riser weir type (flat, rectangular notch, V-notch, or Sutro), and the orifice diameter and height.



The second option is that the flow split can be based on a flow threshold. The user sets the flow threshold value (cfs) for exit 1 at which flows in excess of the threshold go to exit 2. For example, if the flow threshold is set to 5 cfs then all flows less than or equal to 5 cfs go to exit 1. Exit 2 gets only the excess flow above the 5 cfs threshold (total flow minus exit 1 flow).

TIME SERIES



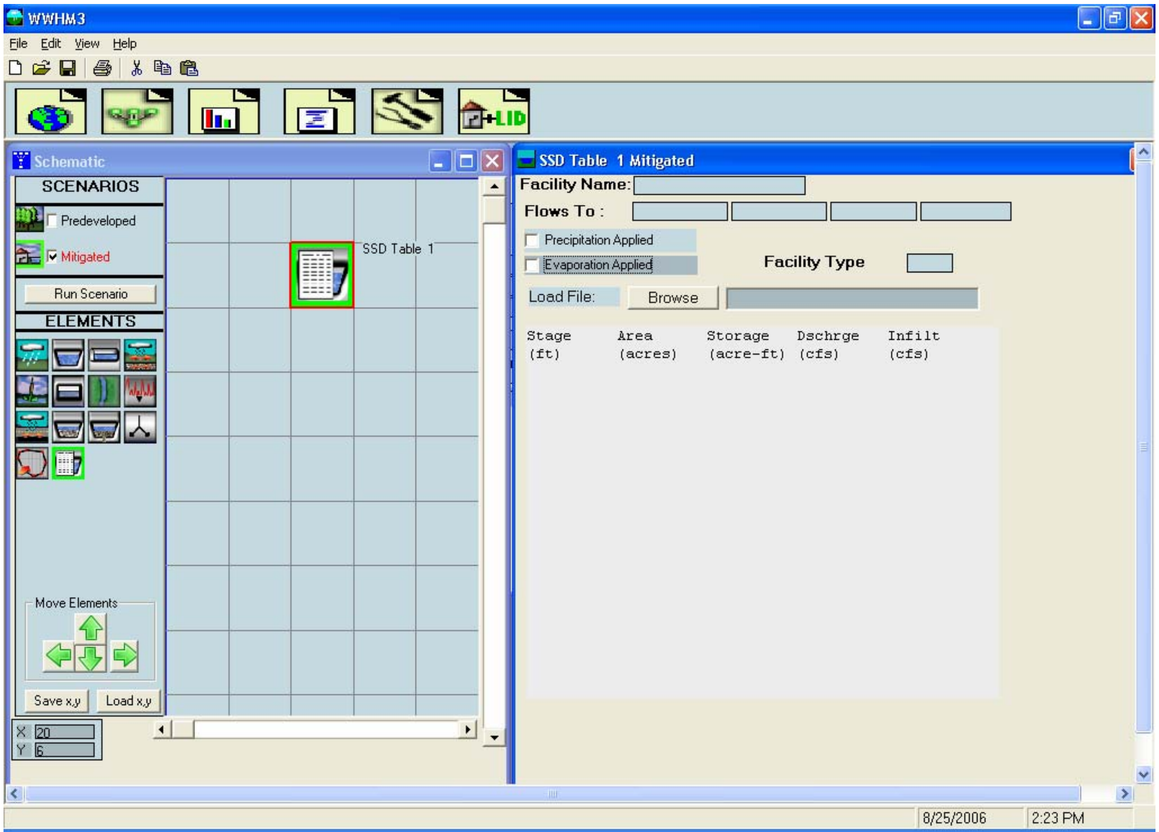
The WWHM3 uses time series of precipitation, evaporation, and runoff stored in its database (HSPF WDM file). The user has the option to create or use a time series file external from the WWHM3 in the WWHM3. This may be a time series of flow values created by another HSPF model. An example is offsite runoff entering a project site. If this offsite runoff is in an existing WDM file and is the same period as the WWHM3 data and the same simulation time step (hourly) then it can be linked to the WWHM3 model using the Time Series element.

To link the external time series to the WWHM3 the user clicks on the Load WDM button and identifies the external WDM file. The external WDM's individual time series files are shown in the box immediately below the Load WDM button and under the box heading "Choose Input Dataset". The selected input dataset is the time series that will be used by the WWHM3.

The user also has the option of modifying and/or copying time series files using the options shown in the Functions box. These options are: add, subtract, apply factor (multiply), copy, raise to a power, select a threshold greater than, and select a threshold less than. Once a specific option is selected then by clicking on Run Analysis the time series is appropriately modified.

The user can also output a time series generated by the WWHM3 using the options shown in the Time Series Out box. The user chooses the appropriate WDM file (WWHM3 can have a maximum of five separate WDM files, but usually has just one) and the time series (output dataset) within the WDM file. This output time series can be saved and later used as an input time series in other WWHM3 models, if appropriate.

SSD TABLE



The SSD Table is a stage-storage-discharge table externally produced by the user and is identical in format to the stage-storage-discharge tables generated internally by the WWHM3 for ponds, vaults, tanks, and channels.

The easiest way to create a SSD Table outside of the WWHM3 is to use a spreadsheet with a separate column for stage, surface area, storage, and discharge (in that order). Save the spreadsheet file as a space or comma-delimited file. A text file can also be created, if more convenient.

The SSD Table must use the following units:
Stage: feet
Surface Area: acres
Storage: acre-feet
Discharge: cubic feet per second (cfs)

A fifth column can be used to create a second discharge (cfs). This second discharge can be infiltration or a second surface discharge.

Certain rules apply to the SSD Table whether it is created inside or outside of the WWHM3. These rules are:

1. Stage (feet) must start at zero and increase with each row. The incremental increase does not have to be consistent.

2. Storage (acre-feet) must start at zero and increase with each row. Storage values should be physically based on the corresponding depth and surface area, but the WWHM3 does not check externally generated storage values.

3. Discharge (cfs) must start at zero. Discharge does not have to increase with each row. It can stay constant or even decrease. Discharge cannot be negative. Discharge should be based on the outlet structure's physical dimensions and characteristics, but the WWHM3 does not check externally generated discharge values.

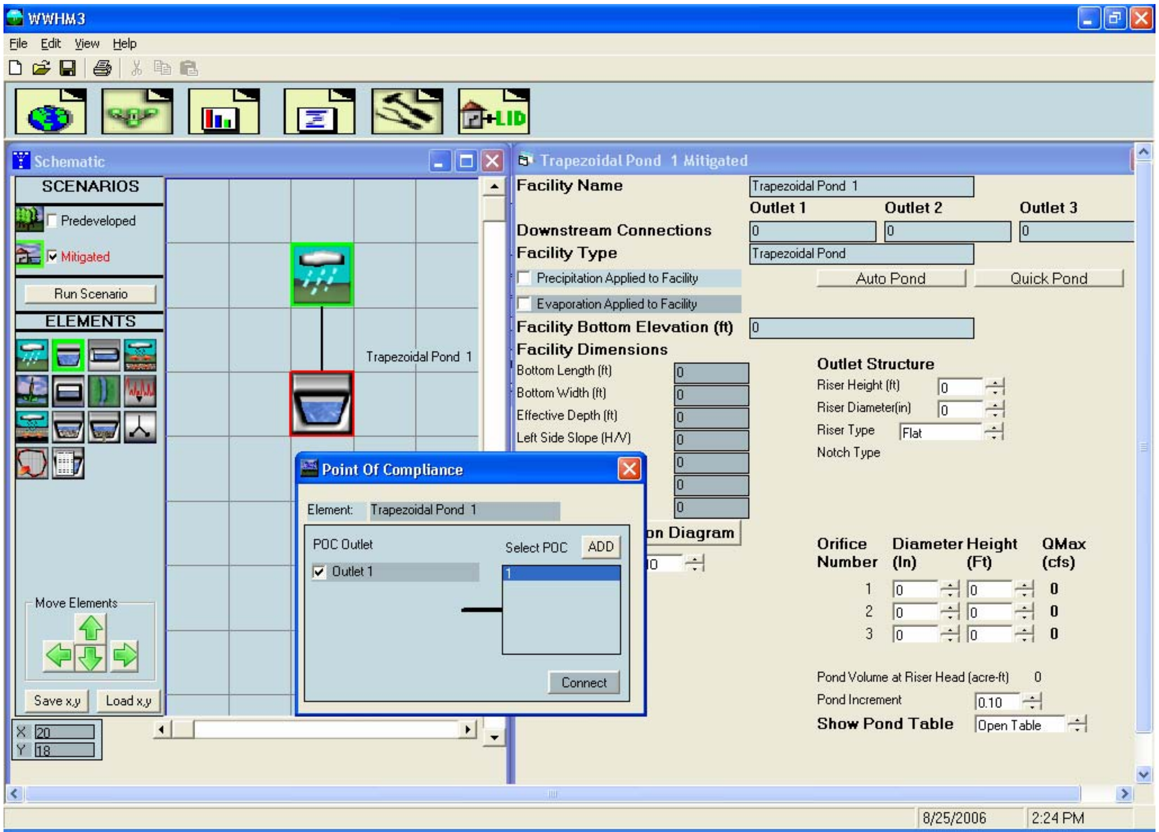
4. Surface area (acres) is only used if precipitation to and evaporation from the facility are applied.

To input an externally generated SSD Table, first create and save the table outside of the WWHM3. Use the Browse button to locate and load the file into the WWHM3.

POINT OF COMPLIANCE

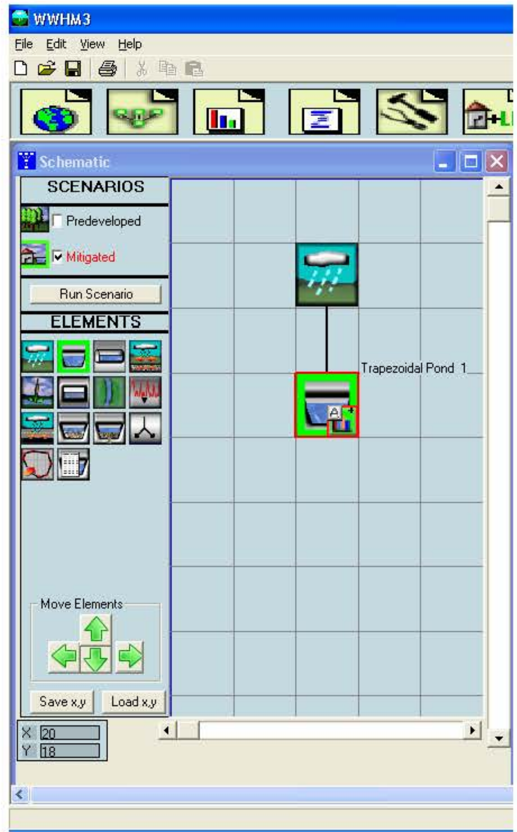
WWHM3 allows for multiple points of compliance (maximum of 99) in a single project. A point of compliance is defined as the location at which the Predeveloped and Mitigated flows will analyzed for compliance with Ecology's flow control standard.

WWHM2 had a point of compliance icon or element; WWHM3 does not.

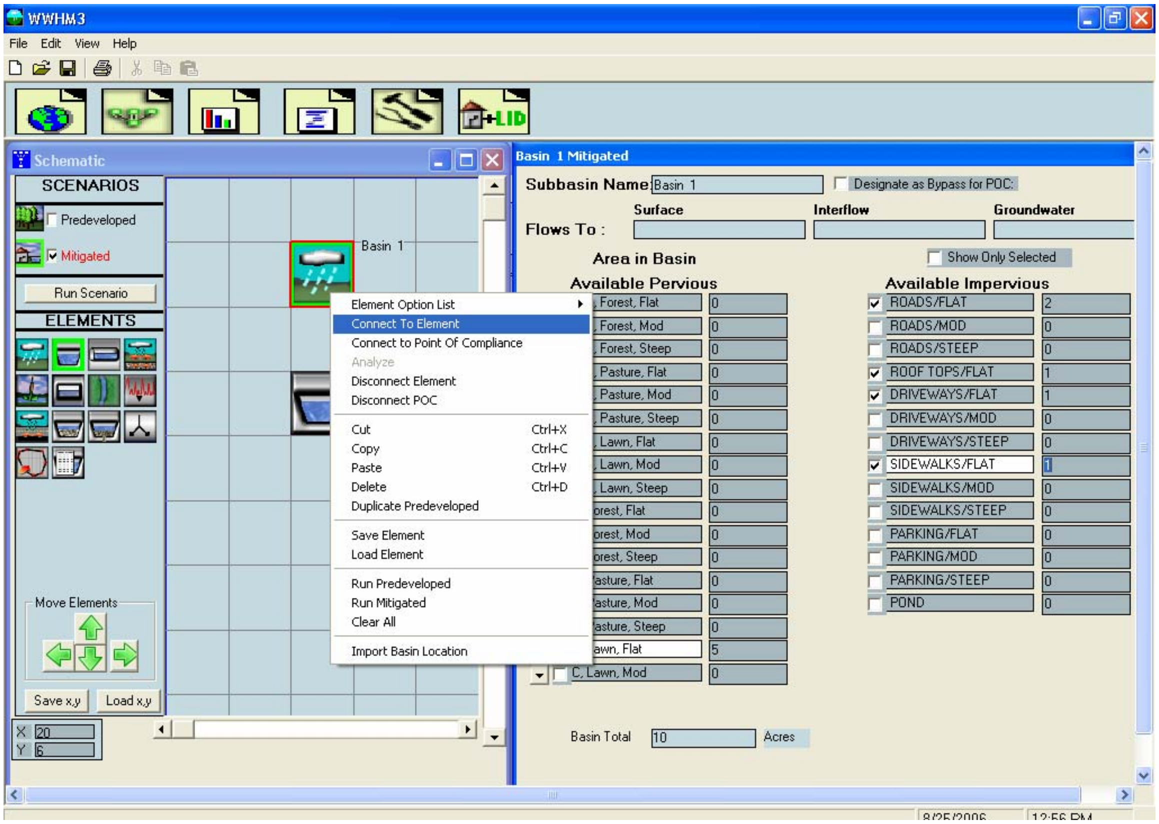


The point of compliance is selected by right clicking on the element at which the compliance analysis will be made. In the example above, the point of compliance analysis will be conducted at the outlet of the trapezoidal pond.

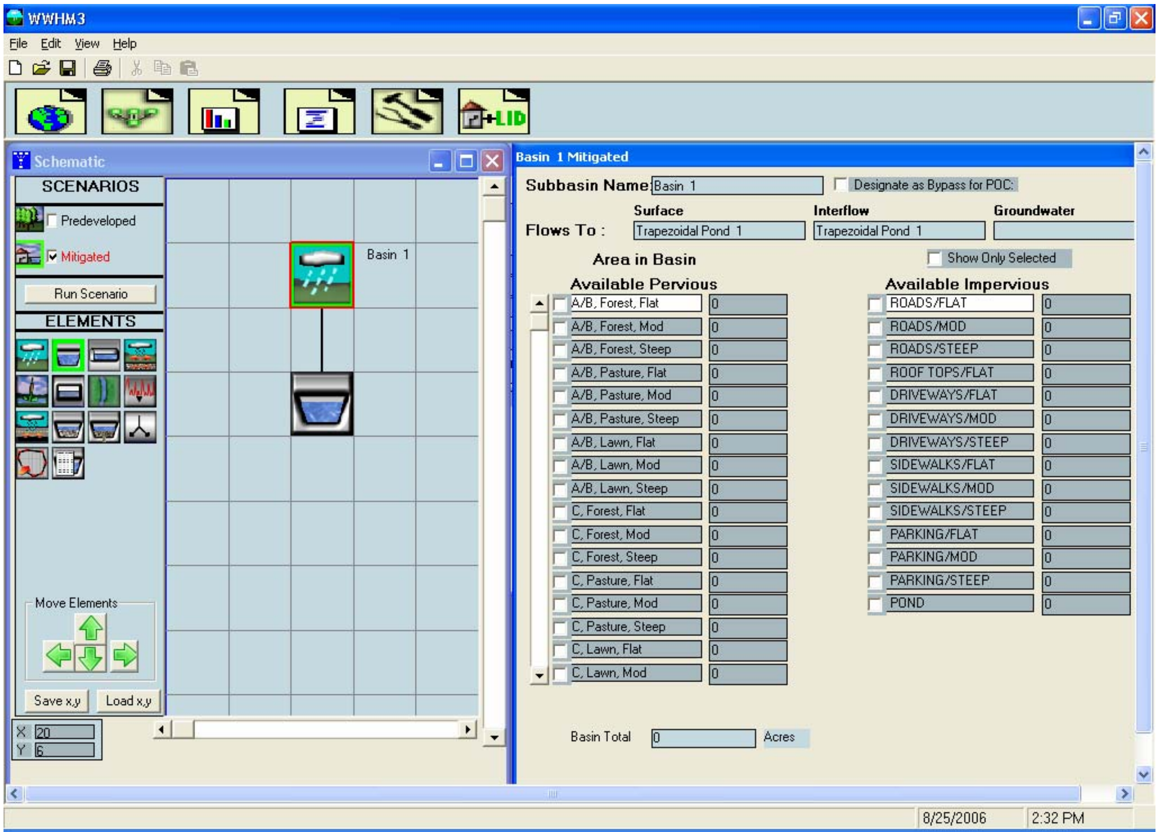
Once the point of compliance has been selected the element is modified on the Schematic screen to include a small box with the letter “A” (for Analysis) in the lower right corner. This identifies the outlet from this element as a point of compliance.



CONNECTING ELEMENTS

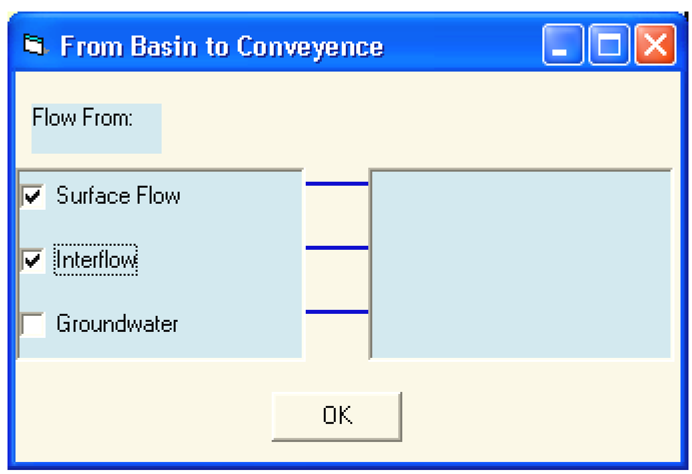


Elements are connected by right clicking on the upstream element (in this example Basin 1) and selecting and then left clicking on the Connect To Element option. By doing so the WWHM3 extends a line from the upstream element to wherever the user wants to connect that element.

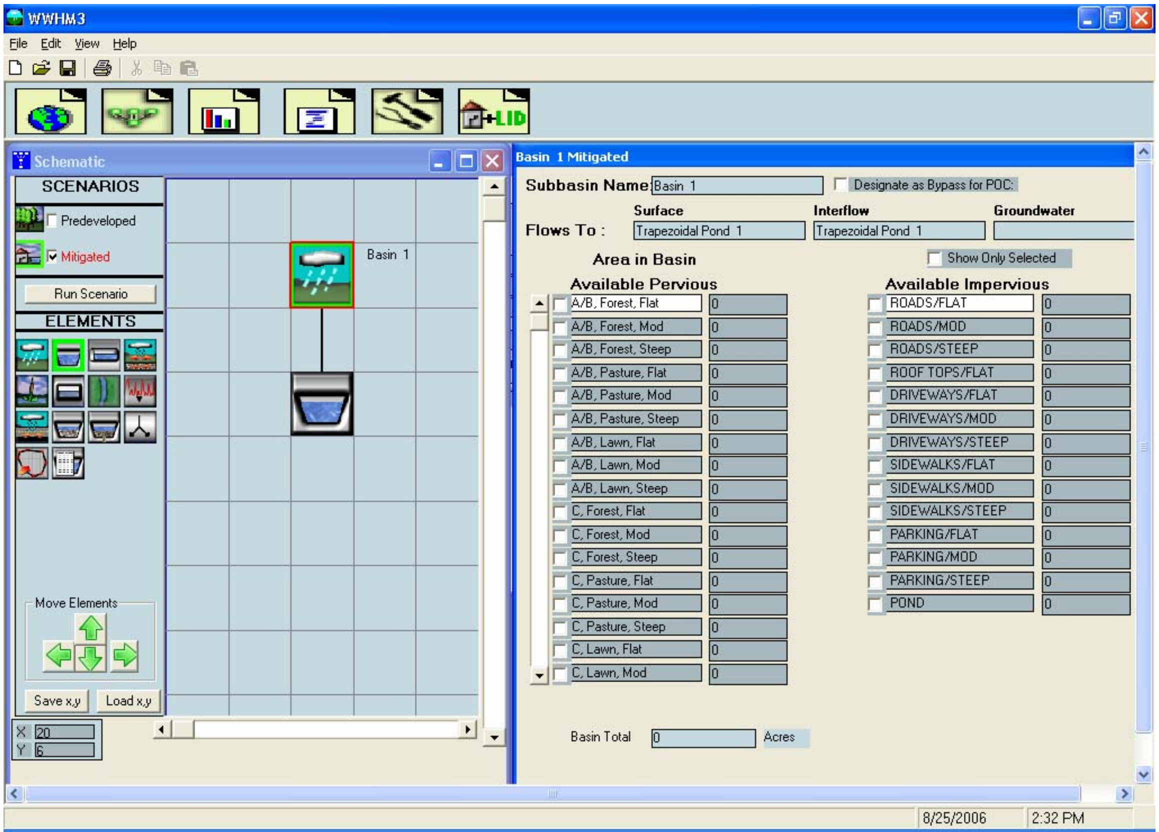


The user extends the connection line to the downstream element (in this example, a pond) and left clicks on the destination element. This action brings up the From Basin to Conveyance box that allows the user to specify which runoff components to route to the downstream element.

Stormwater runoff is defined as surface flow + interflow. Both boxes should be checked. Groundwater should not be checked for the standard land development mitigation analysis. Groundwater should only be checked when there is observed and documented base flow occurring from the upstream basin.

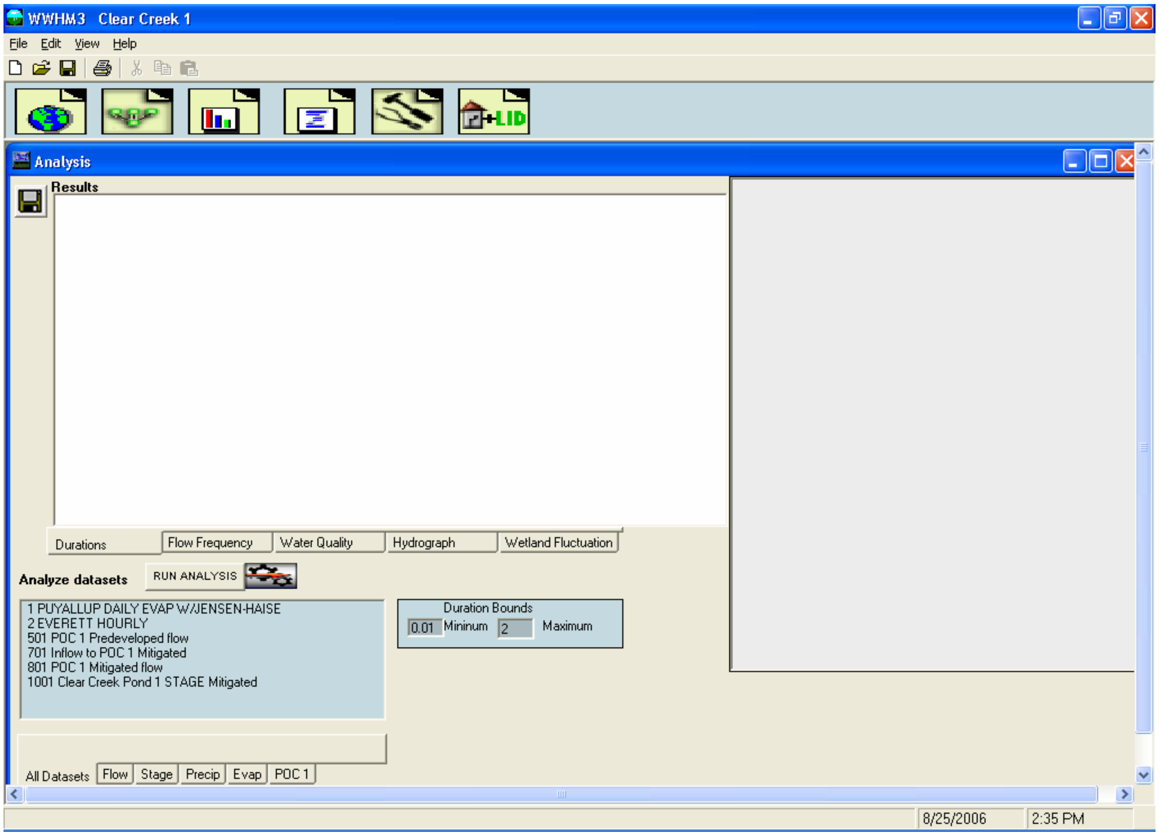


After the appropriate boxes have been checked click the OK button.

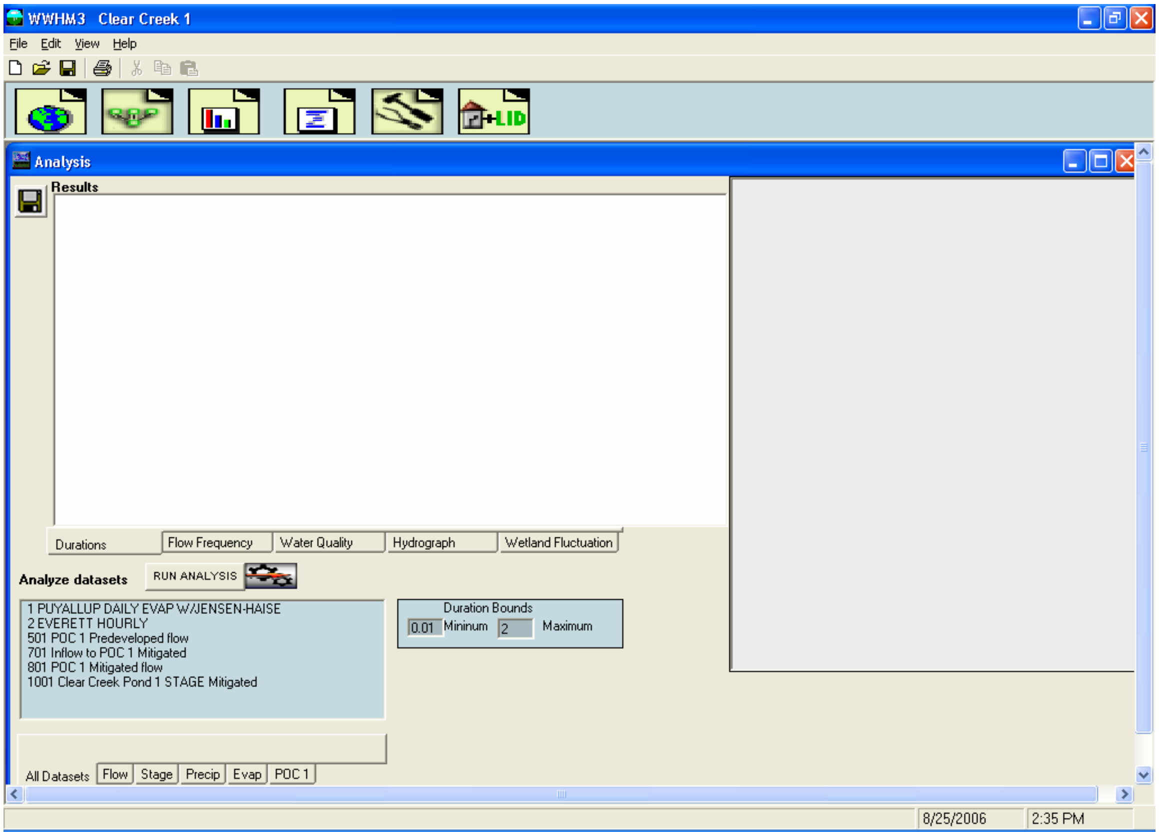


The final screen will look like the above screen. The basin information screen on the right will show that Basin 1 surface and interflow flows to Trapezoidal Pond 1 (groundwater is not connected).

ANALYSIS SCREEN

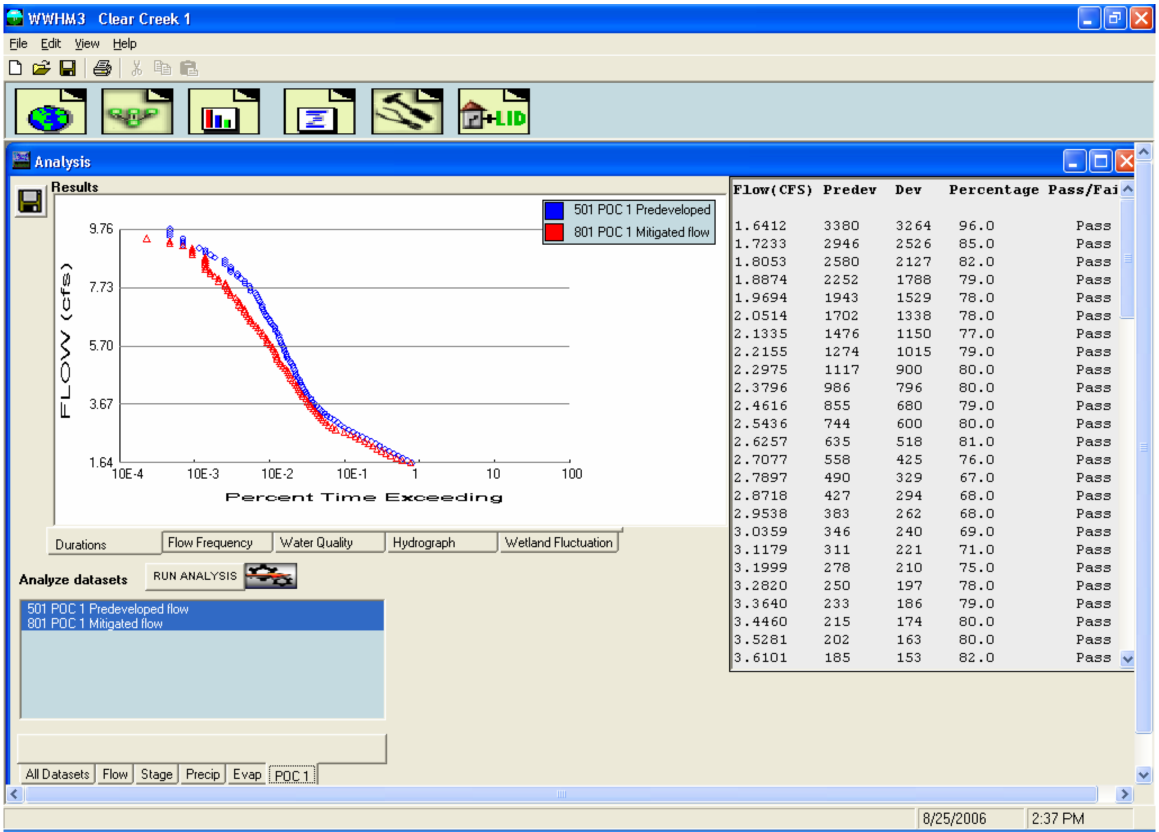


The Analysis tool bar button (third from the left) brings up the Analysis screen where the user can look at the results. The Analysis screen allows the user to analyze and compare flow durations, flow frequency, water quality, hydrographs, and wetland fluctuations.



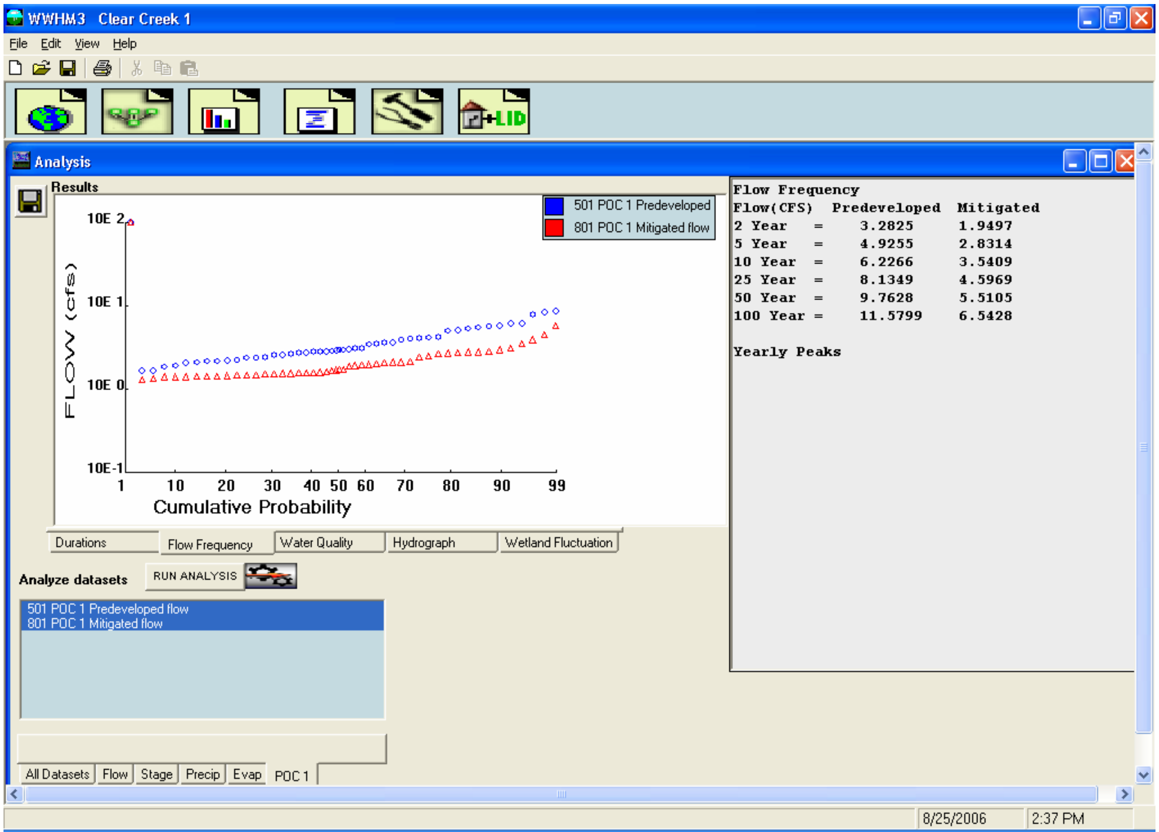
The user can analyze all time series datasets or just flow, stage, precipitation, evaporation, or point of compliance (POC) flows by selecting the appropriate tab below the list of the different datasets available for analysis.

Flow Duration



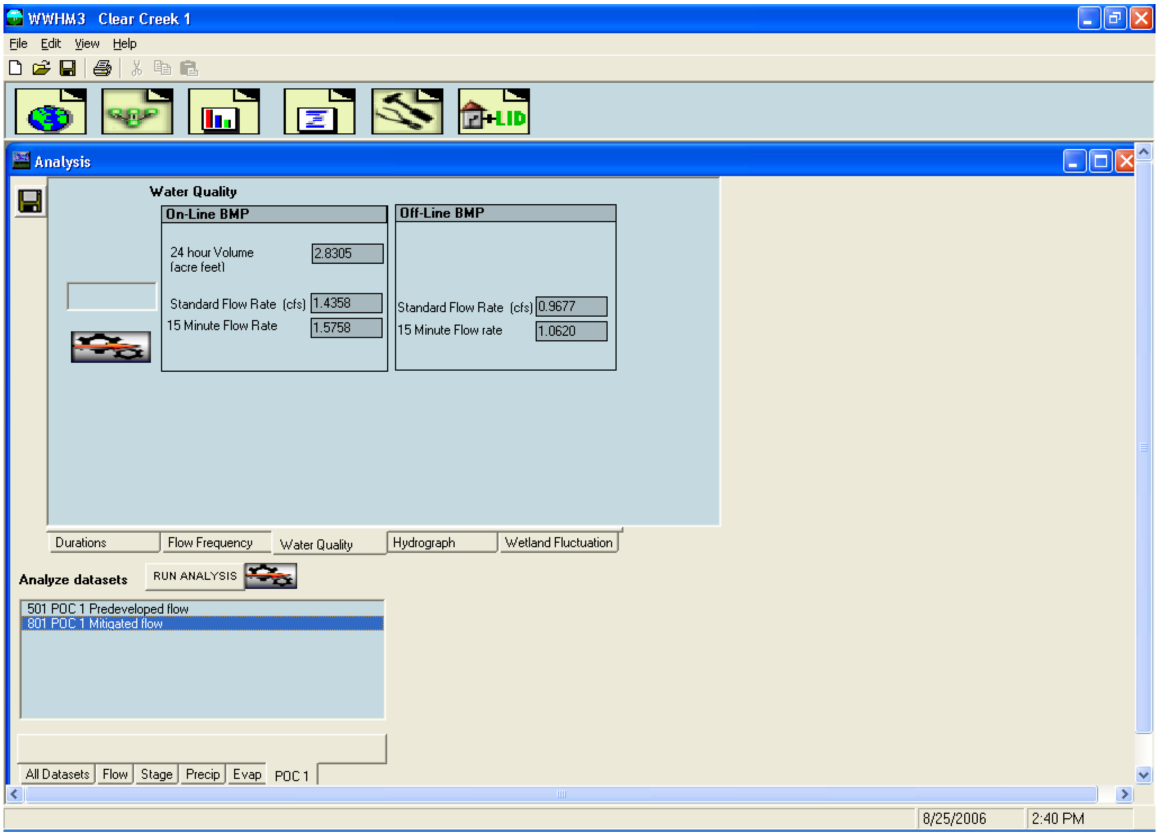
Flow duration at the point of compliance (POC 1) is the most common analysis. A plot of the flow duration values is shown on the left, the flow values on the right.

Flow Frequency



Flow frequency plots are shown on the left and the 2-, 5-, 10-, 25-, 50-, and 100-year frequency values are on the right. Flow frequency calculations are based on a Log Pearson Type III distribution of yearly peak flow values.

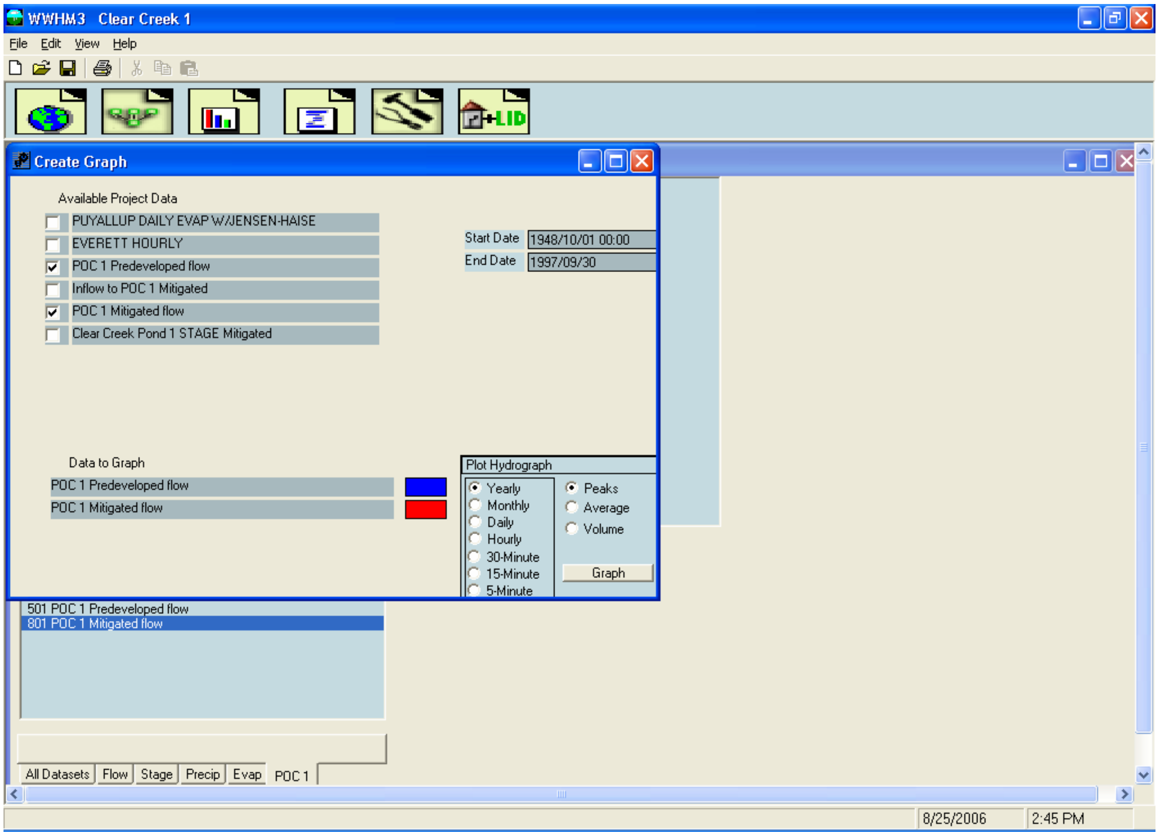
Water Quality



The water quality screen allows the user to compute the target volumes and flows for offline and online water quality facilities. Select the dataset 801 POC 1 Mitigated flow for the water quality analysis. Click on the Gear button on the left side of the Water Quality analysis results for the WWHM3 to compute volumes and flows based on Ecology's water quality facility sizing criterion (91% of total runoff volume) or a criterion selected by the user via View, Options, Scaling Factor Water Quality.

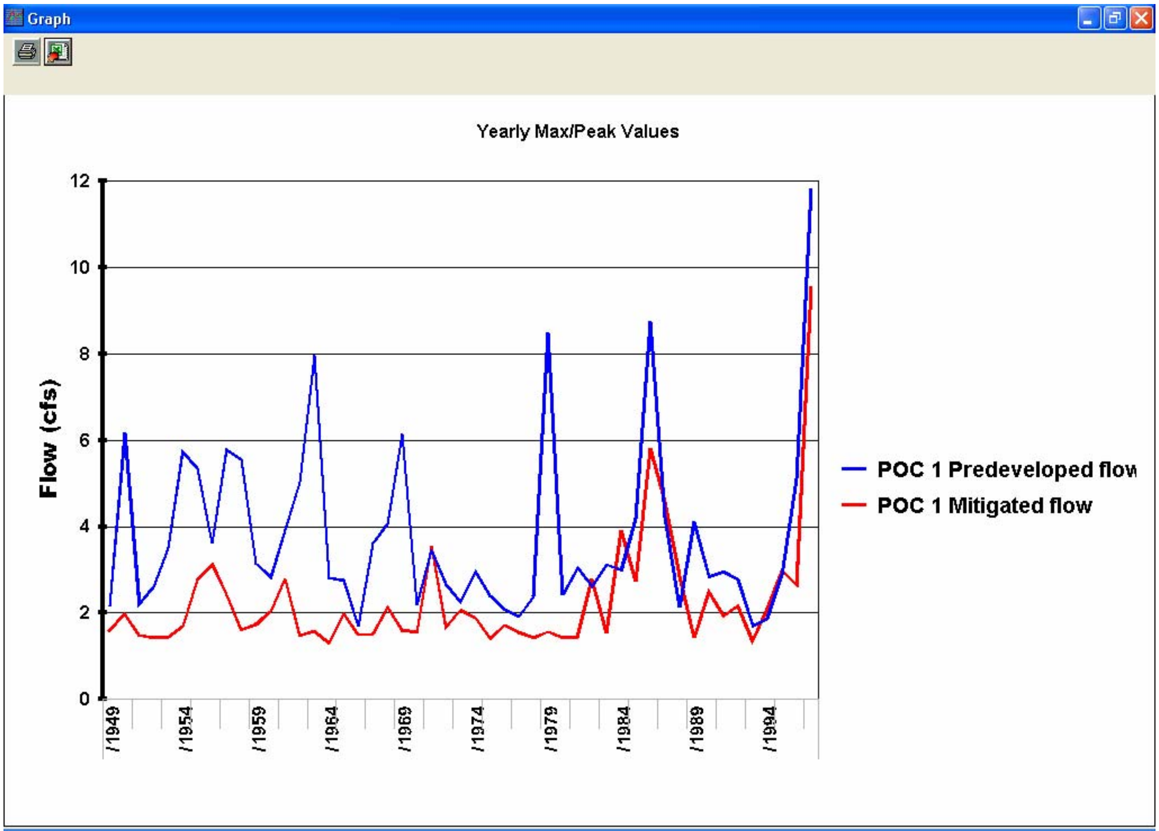
An online water quality facility is downstream of the project flow control facility; all of the runoff is routed through an online facility. An offline facility receives only a portion of the total runoff.

Hydrographs



The user can graph/plot any or all time series data by selecting the Hydrograph tab. The Create Graph screen is shown and the user can select the time series to plot, the time interval (yearly, monthly, daily, or hourly), and type of data (peaks, average, or volume).

The selected time series are shown. To graph the selected time series the user clicks on the Graph button.



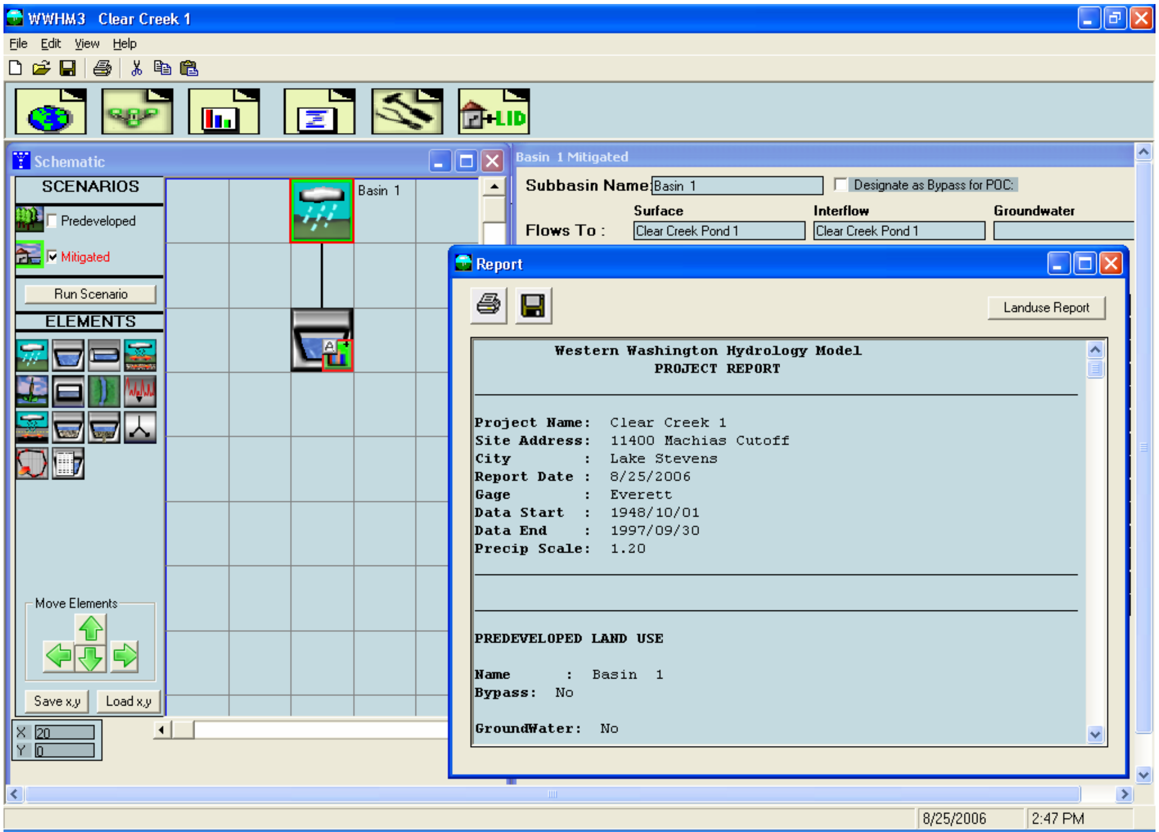
The hydrograph shows the yearly maximum/peak flow values for each time series for the entire simulation period (in this example, from 1949 through 1999).

The graph can be either saved or printed.

Wetland Fluctuation

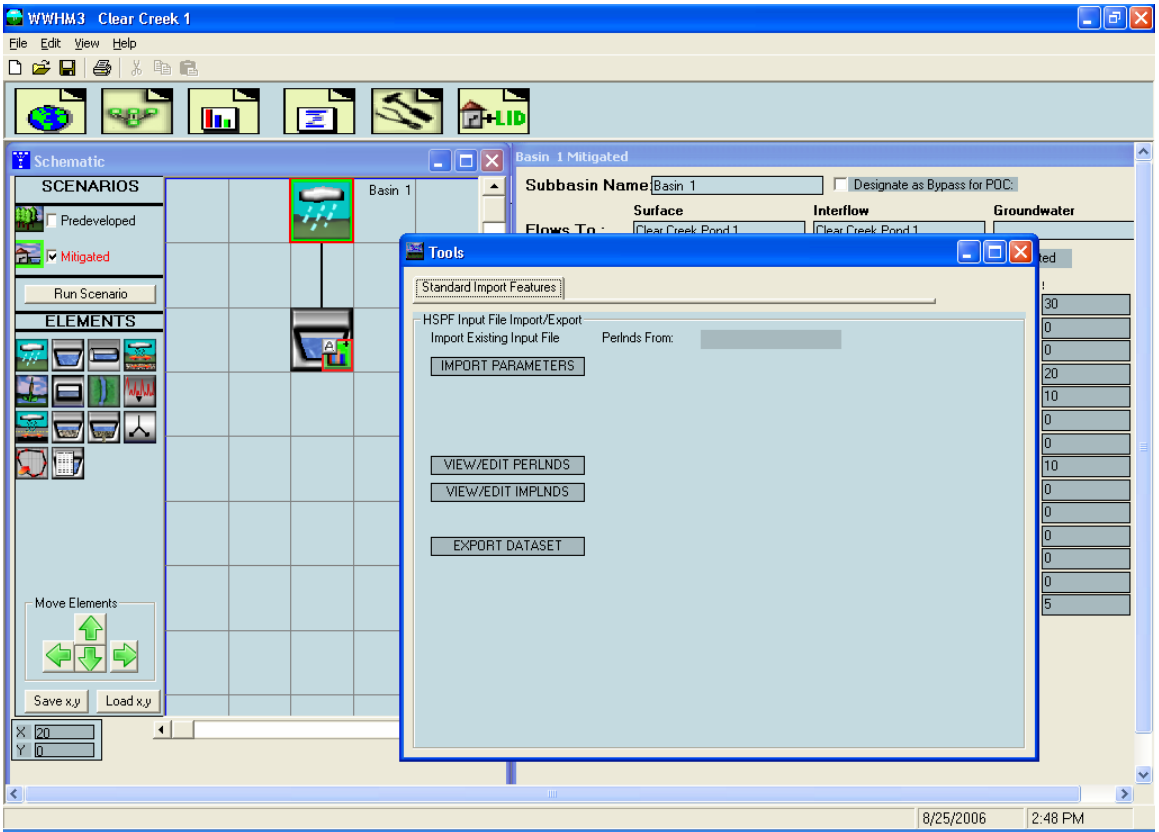
This option is still under construction pending selection of appropriate wetland fluctuation criteria by Washington State Department of Ecology wetland specialists.

REPORTS SCREEN



The Reports tool bar button (fourth from the left) brings up the Report screen where the user can look at all of the project input and output. The project report can be saved or printed.

TOOLS SCREEN

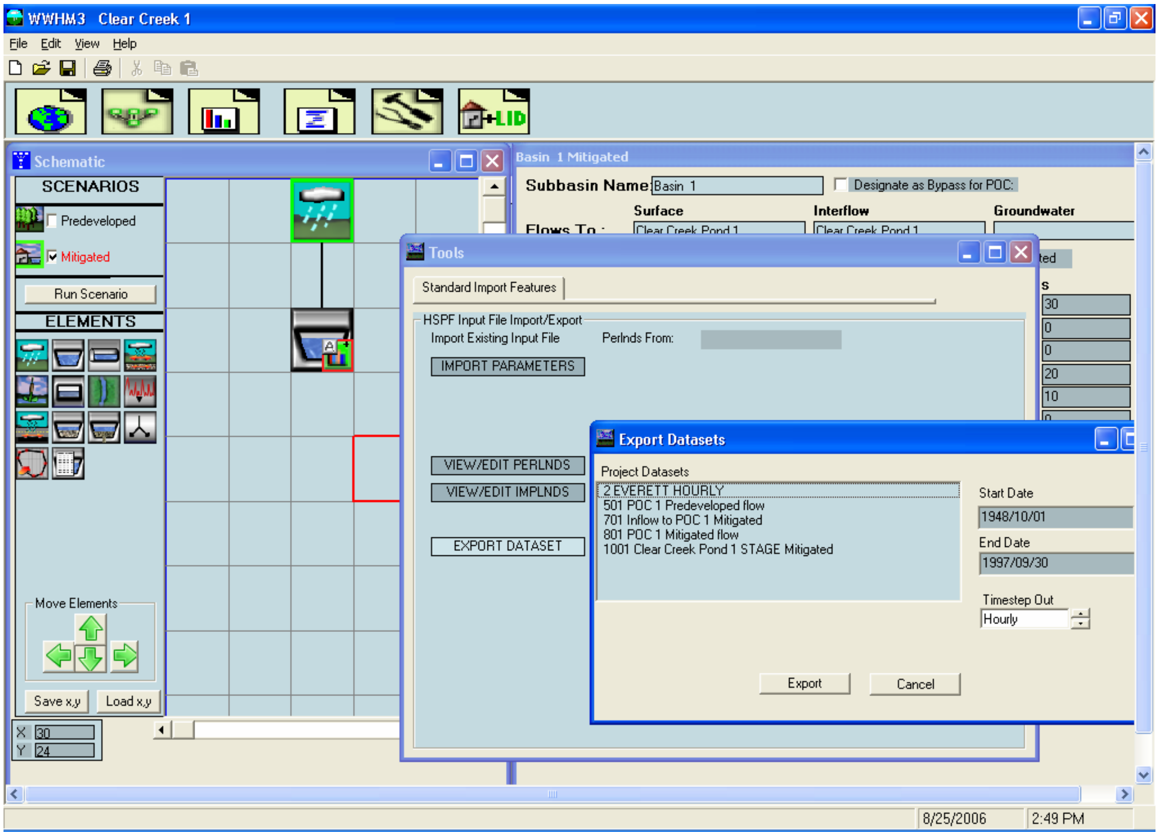


The Tools screen is accessed with the Tools tool bar (second from the right). The two purposes of the Tools screen are:

(1) To allow users to import HSPF PERLND from existing HSPF UCI files and/or view and edit WWHM3 PERLND parameter values.

(2) To allow users to export time series datasets.

To export a time series dataset click on the Export Dataset box.



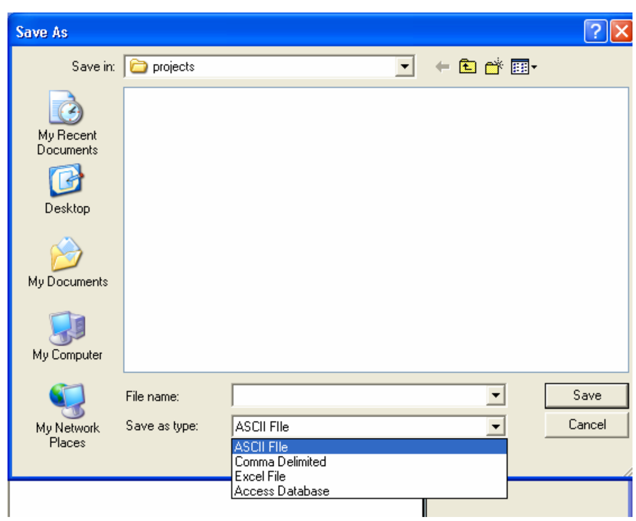
The list of available time series datasets will be shown. The user can select the start and end dates for the data they want to export.

The time step (hourly, daily, monthly, yearly) can also be specified. If the user wants daily, monthly, or yearly data the user is given the choice of either selecting the maximum, minimum, or the sum of the hourly values.

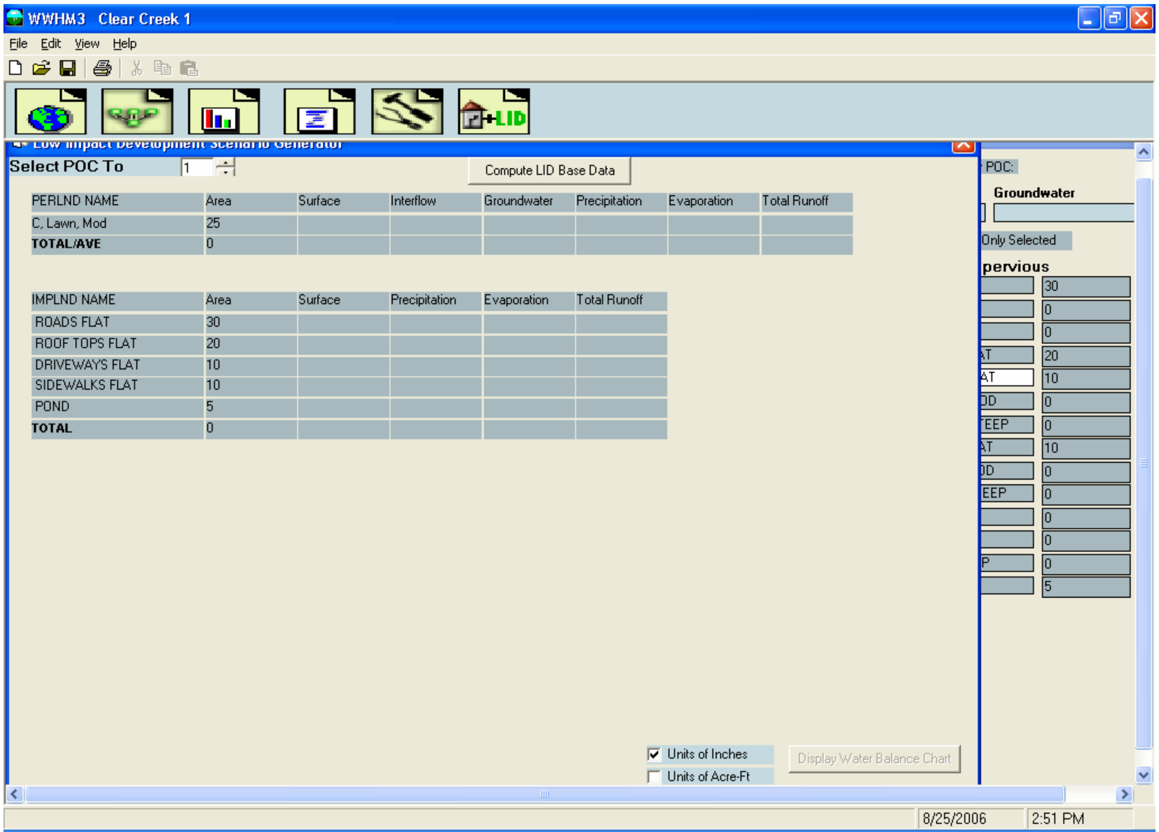
Click the Export button.

The user provides a file name and the format or type of file. The file type can be ASCII, comma delimited, Excel spreadsheet, or Access database.

Click Save to save the exported time series file.

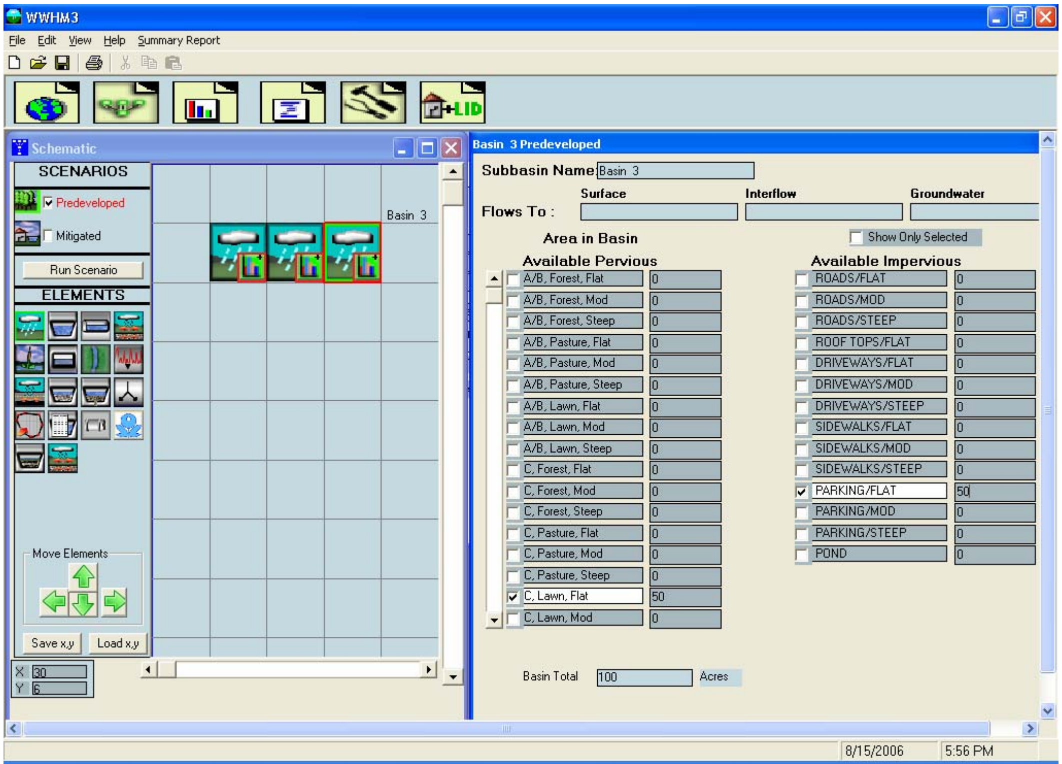


LID ANALYSIS SCREEN



The LID tool bar button (farthest on the right) brings up the Low Impact Development Scenario Generator screen.

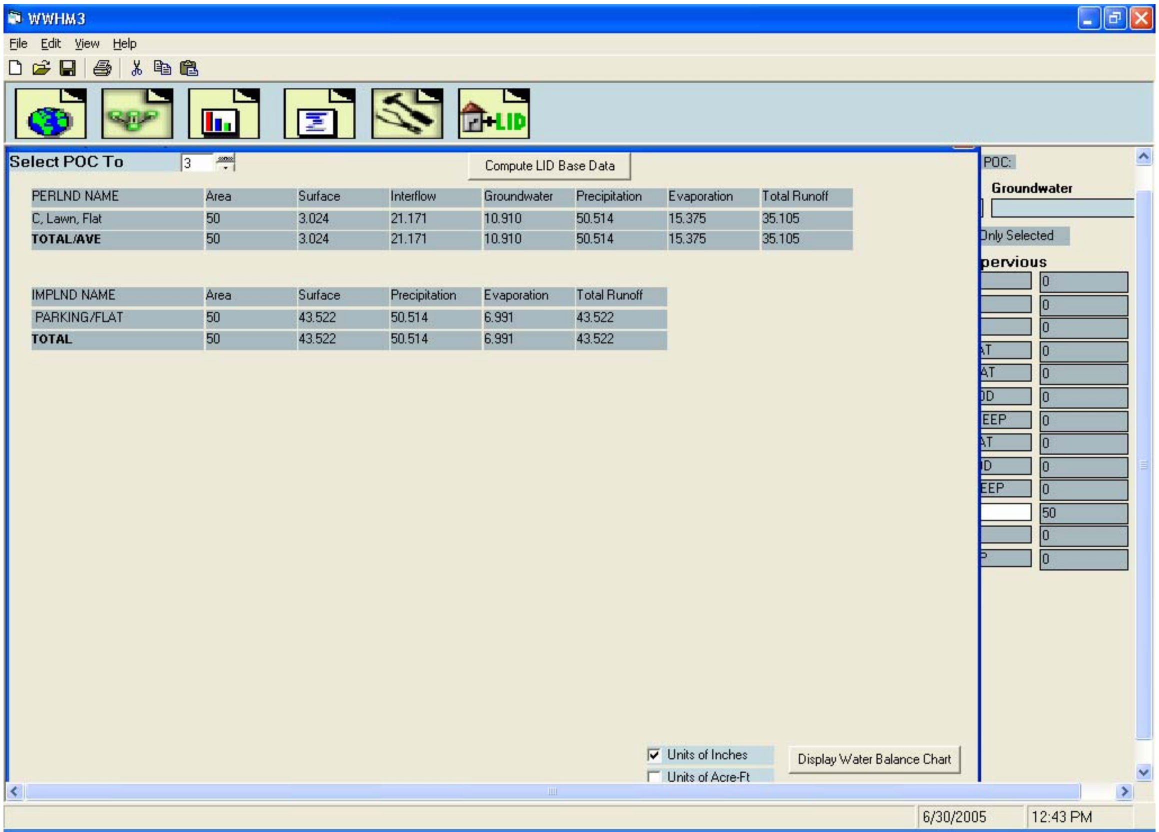
The LID scenario generator can be used to compare the amount of runoff from different land types and combinations. The user can quickly see how changing the land use affects surface runoff, interflow, groundwater, and evapotranspiration.



The easiest way to compare different land use scenarios is to place all of them on the same Schematic Editor screen grid. Each basin can then represent a different land use scenario. Because the LID scenario generator only compares runoff volume there is no need to do any routing through a conveyance system or stormwater facility.

For this example the three basins are assigned the following land uses:
Basin 1: 100 acres C, Forest, Flat
Basin 2: 100 acres C, Lawn, Flat
Basin 3: 50 acres C, Lawn, Flat; 50 acres Parking Flat

Each basin is assigned a different POC (point of compliance) for the LID analysis.



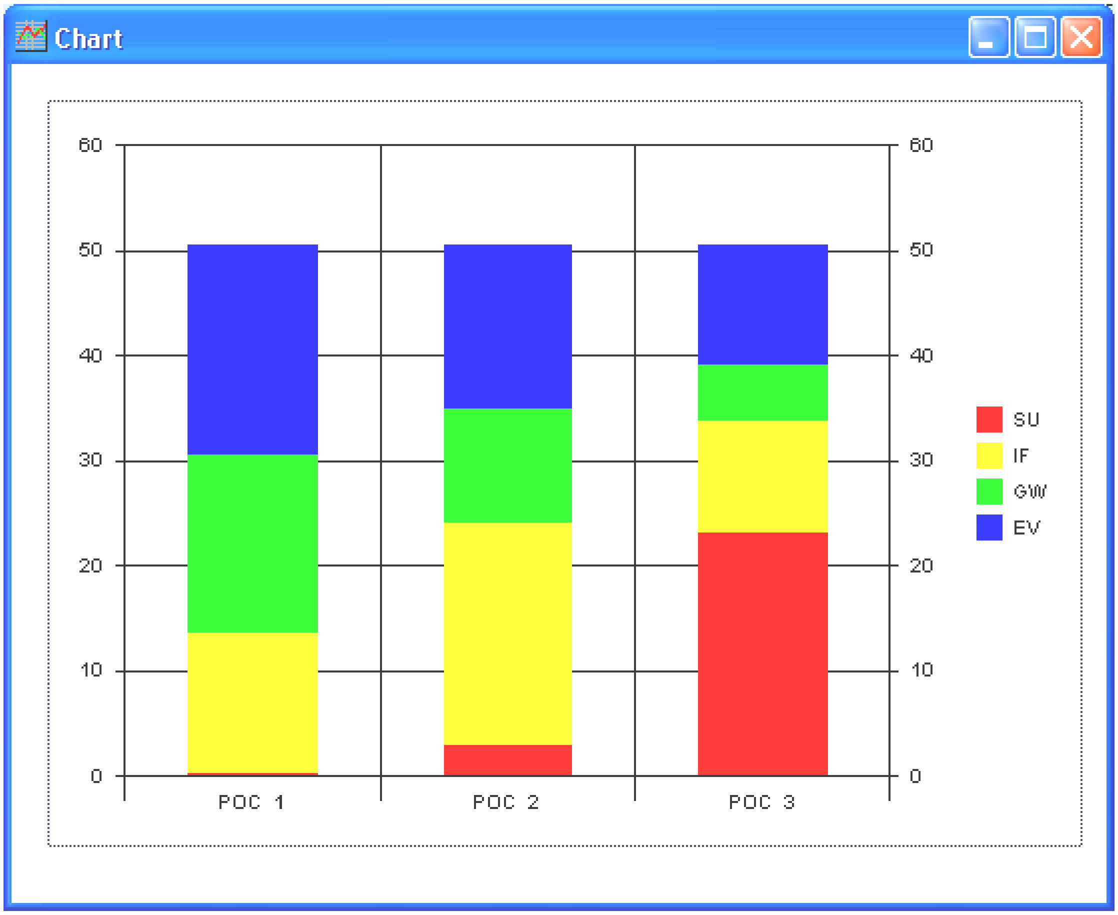
Click on the Compute LID Base Data button to generate the LID analysis data and summarize the surface runoff, interflow, groundwater, precipitation, evaporation, and total runoff for all of the basins. The results will be shown for each basin in terms of its POC.

For the pervious portion of Basin 1 (50 acres of C, Lawn, Flat) the distribution of the precipitation is:
Surface runoff = 3.024 inches per year
Interflow = 21.171 inches per year
Groundwater = 10.910 inches per year
Evaporation = 15.375 inches per year

To look at the other basins click on the Select POC To arrow and select the basin of interest.

The LID analysis results can be presented in terms of either inches per year or acre-feet per year by checking the appropriate box in the lower right portion of the LID analysis screen.

To compare the different scenarios side-by-side in a graphical format click on the Display Water Balance Chart.

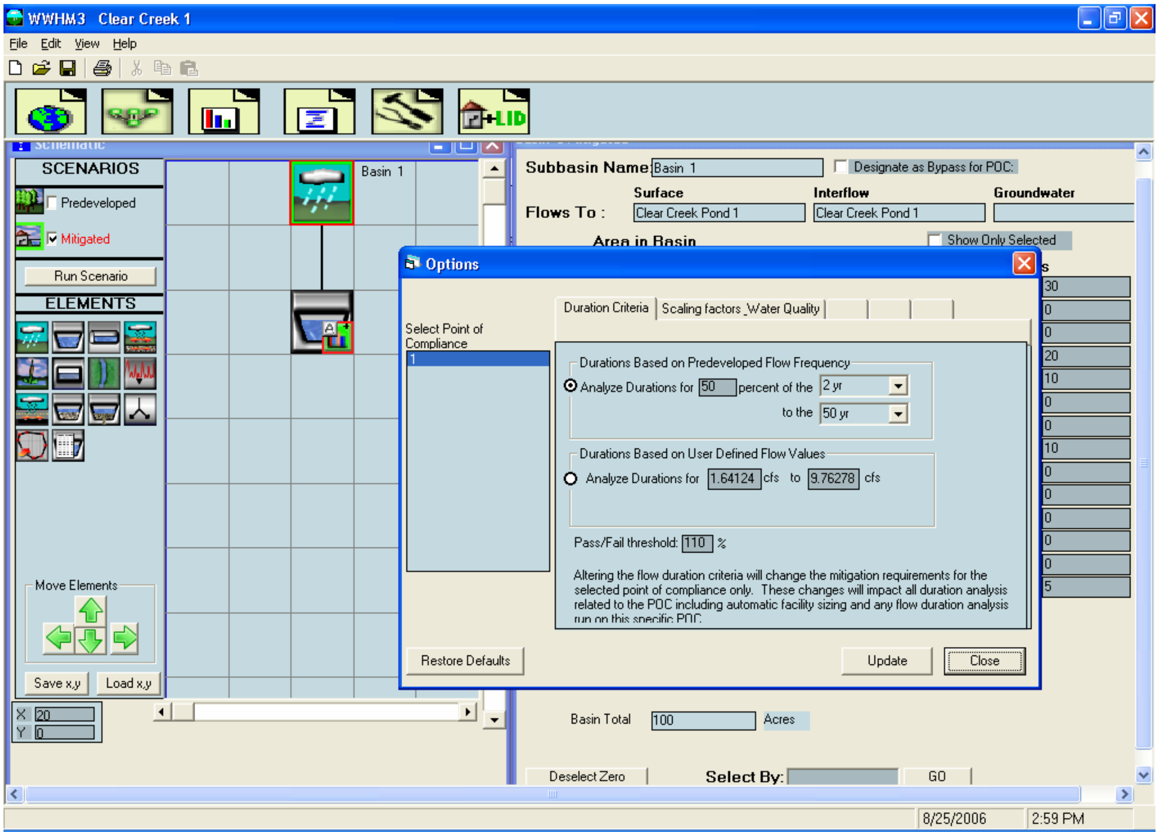


The water balance chart graphically displays the runoff distribution for all three land use scenarios side-by-side.

The bottom red is the surface runoff. Above in yellow is interflow; then green for groundwater and blue for evaporation. Basin 1 (Scenario 1) is all forest and produces the least amount of surface runoff and interflow (the sum of surface and interflow is the total stormwater runoff). Basin 2 is all lawn; it produces more surface runoff and interflow than Basin 1. Basin 3 is 50% lawn and 50% impervious and produces the largest amount of surface runoff and interflow and the smallest amount of groundwater and evaporation.

A maximum of seven scenarios can be graphed at one time.

OPTIONS



Options can be accessed by going to View, Options. This will bring up the Options screen and the ability to modify the duration standards, water quality scaling factors, and the criteria checker.

Duration Criteria

The Washington State Department of Ecology's flow control standard is based on flow duration. The duration criteria are:

1. If the post-development flow duration values exceed any of the predevelopment flow levels between 50% and 100% of the two-year predevelopment peak flow values (100 Percent Threshold) then the flow control standard requirement has not been met.

2. If the post-development flow duration values exceed any of the predevelopment flow levels between 100% of the two-year and 100% of the 50-year predevelopment peak flow values more than 10 percent of the time (110 Percent Threshold) then the flow control standard has not been met.

3. If more than 50 percent of the flow duration levels exceed the 100 percent threshold then the flow control standard has not been met.

The duration criteria in the WWHM3 can be modified by the user if appropriate and the permitting and reviewing agency allows.

The user can conduct the duration analysis using either (1) durations based on Predeveloped flow frequency, or (2) durations based on user defined flow values.

If using durations based on Predeveloped flow frequency the percent of the lower limit can be changed from the default of the 2-year flow event to a higher or lower percent value. The lower and upper flow frequency limits (2-year and 50-year) also can be changed.

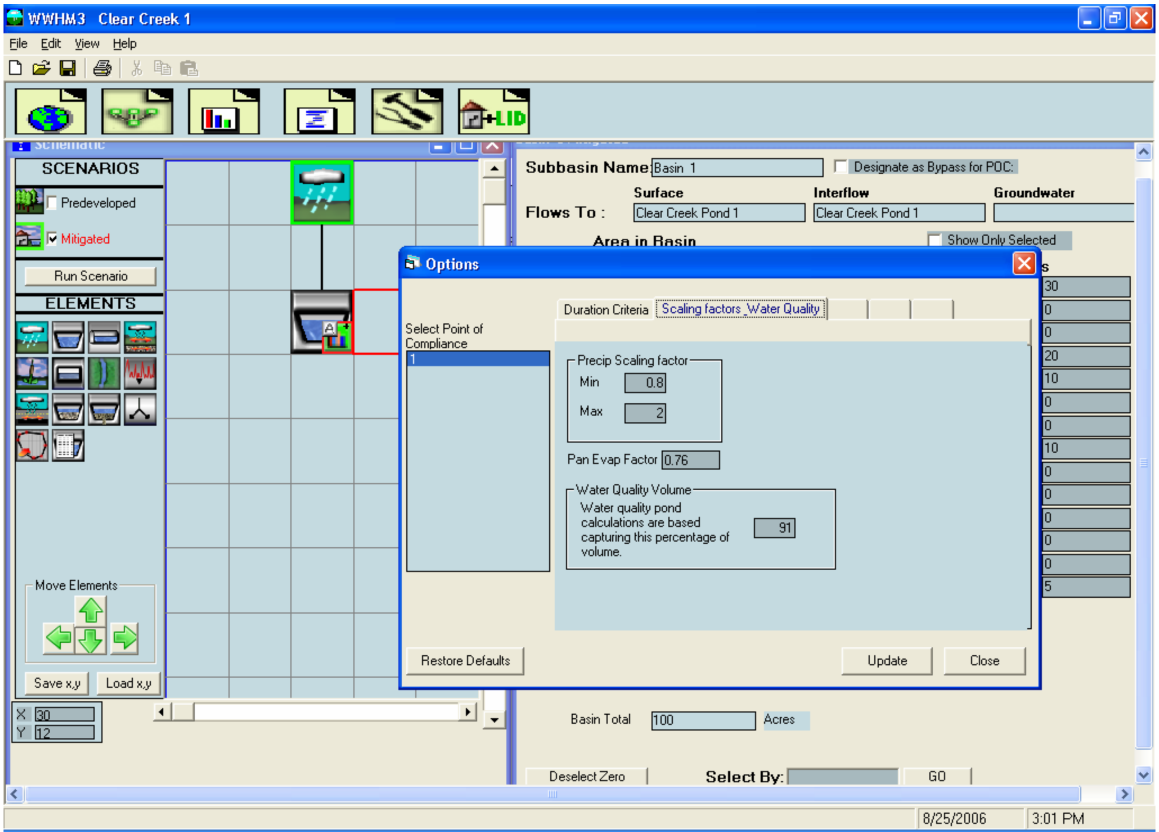
If using durations based on user defined flow values click on that option and input the lower and upper flow values.

The default pass/fail threshold is 110%. This value can be changed by the user.

The duration standards can be changed for a single point of compliance. Click on the Update button once all of the changes have been made. To return to the default values click on the Restore Defaults button.

Any change(s) to the default duration standards must be approved by the reviewing and permitting agencies.

Scaling Factors_Water Quality



The user can change the scaling factors for precipitation (minimum and maximum) and pan evaporation. Neither should be changed without agency approval.

The water quality volume percentage is set to 91% of the total runoff volume. If allowed, this percent value can be changed by the user.

Click on the Update button once all of the changes have been made. To return to the default values click on the Restore Defaults button.

APPENDIX A: DEFAULT WWHM3 HSPF PERVIOUS PARAMETER VALUES

The default WWHM3 HSPF pervious parameter values are found in the WWHM3 file defaultpers.uci.

The default WWHM3 HSPF pervious parameter values are based on the USGS report:
Dinicola, R.S. 1990. Characterization and Simulation of Rainfall-Runoff Relations for Headwater Basins in Western King and Snohomish Counties, Washington. Water-Resources Investigations Report 89-4052. U.S. Geological Survey. Tacoma, WA.

For some parameters the default WWHM3 HSPF pervious parameter values have been modified from the values listed in the USGS report. These modifications are based on the professional judgment and experience of Clear Creek Solutions staff in modeling Western Washington watersheds with HSPF.

HSPF parameter documentation is found in the document:
Bicknell, B.R., J.C. Imhoff, J.L. Kittle Jr, T.H. Jobes, and A.S. Donigian Jr. 2001. Hydrological Simulation Program – Fortran, User’s Manual for Version 12. AQUA TERRA Consultants. Mountain View, CA.

Table 1. WWHM3 Pervious Land Types

PERLND No.	Soil	Vegetation/Surface	Slope
1	A/B	Forest	Flat
2	A/B	Forest	Moderate
3	A/B	Forest	Steep
4	A/B	Pasture	Flat
5	A/B	Pasture	Moderate
6	A/B	Pasture	Steep
7	A/B	Lawn	Flat
8	A/B	Lawn	Moderate
9	A/B	Lawn	Steep
10	C	Forest	Flat
11	C	Forest	Moderate
12	C	Forest	Steep
13	C	Pasture	Flat
14	C	Pasture	Moderate
15	C	Pasture	Steep
16	C	Lawn	Flat
17	C	Lawn	Moderate
18	C	Lawn	Steep
19	Saturated	Forest	Flat
20	Saturated	Forest	Moderate
21	Saturated	Forest	Steep
22	Saturated	Pasture	Flat
23	Saturated	Pasture	Moderate
24	Saturated	Pasture	Steep
25	Saturated	Lawn	Flat
26	Saturated	Lawn	Moderate
27	Saturated	Lawn	Steep
28	C	Impervious dispersed on Lawn	Flat
29	C	Impervious dispersed on Lawn	Moderate
30	C	Impervious dispersed on Lawn	Steep
31	A/B	Impervious infiltrated on Lawn	Flat
32	A/B	Impervious infiltrated on Lawn	Moderate
33	A/B	Impervious infiltrated on Lawn	Steep
34	Saturated	Impervious dispersed on Lawn	Flat
35	Saturated	Impervious dispersed on Lawn	Moderate
36	Saturated	Impervious dispersed on Lawn	Steep

Table 2. WWHM3 HSPF Pervious Parameter Values – Part I

PERLND No.	LZSN	INFILT	LSUR	SLSUR	KVARY	AGWRC
1	5.0	2.00	400	0.050	0.3	0.996
2	5.0	2.00	400	0.100	0.3	0.996
3	5.0	2.00	400	0.150	0.3	0.996
4	5.0	1.50	400	0.050	0.3	0.996
5	5.0	1.50	400	0.100	0.3	0.996
6	5.0	1.50	400	0.150	0.3	0.996
7	5.0	0.80	400	0.050	0.3	0.996
8	5.0	0.80	400	0.100	0.3	0.996
9	5.0	0.80	400	0.150	0.3	0.996
10	4.5	0.08	400	0.050	0.5	0.996
11	4.5	0.08	400	0.100	0.5	0.996
12	4.5	0.08	400	0.150	0.5	0.996
13	4.5	0.06	400	0.050	0.5	0.996
14	4.5	0.06	400	0.100	0.5	0.996
15	4.5	0.06	400	0.150	0.5	0.996
16	4.5	0.03	400	0.050	0.5	0.996
17	4.5	0.03	400	0.100	0.5	0.996
18	4.5	0.03	400	0.150	0.5	0.996
19	4.0	2.00	100	0.001	0.5	0.996
20	4.0	2.00	100	0.010	0.5	0.996
21	4.0	2.00	100	0.100	0.5	0.996
22	4.0	1.80	100	0.001	0.5	0.996
23	4.0	1.80	100	0.010	0.5	0.996
24	4.0	1.80	100	0.100	0.5	0.996
25	4.0	1.00	100	0.001	0.5	0.996
26	4.0	1.00	100	0.010	0.5	0.996
27	4.0	1.00	100	0.100	0.5	0.996
28	4.5	0.03	400	0.050	0.5	0.996
29	4.5	0.03	400	0.100	0.5	0.996
30	4.5	0.03	400	0.150	0.5	0.996
31	5.0	0.80	400	0.050	0.3	0.996
32	5.0	0.80	400	0.100	0.3	0.996
33	5.0	0.80	400	0.150	0.3	0.996
34	4.0	1.00	100	0.001	0.5	0.996
35	4.0	1.00	100	0.010	0.5	0.996
36	4.0	1.00	100	0.100	0.5	0.996

LZSN: Lower Zone Storage Nominal (inches)
INFILT: Infiltration (inches per hour)
LSUR: Length of surface flow path (feet)
SLSUR: Slope of surface flow path (feet/feet)
KVARY: Variable groundwater recession
AGWRC: Active Groundwater Recession Constant (per day)

Table 3. WWHM3 HSPF Pervious Parameter Values – Part II

PERLND No.	INFEXP	INFILD	DEEPFR	BASETP	AGWETP
1	2	2	0	0	0.00
2	2	2	0	0	0.00
3	2	2	0	0	0.00
4	2	2	0	0	0.00
5	2	2	0	0	0.00
6	2	2	0	0	0.00
7	2	2	0	0	0.00
8	2	2	0	0	0.00
9	2	2	0	0	0.00
10	2	2	0	0	0.00
11	2	2	0	0	0.00
12	2	2	0	0	0.00
13	2	2	0	0	0.00
14	2	2	0	0	0.00
15	2	2	0	0	0.00
16	2	2	0	0	0.00
17	2	2	0	0	0.00
18	2	2	0	0	0.00
19	10	2	0	0	0.70
20	10	2	0	0	0.70
21	10	2	0	0	0.70
22	10	2	0	0	0.50
23	10	2	0	0	0.50
24	10	2	0	0	0.50
25	10	2	0	0	0.35
26	10	2	0	0	0.35
27	10	2	0	0	0.35
28	2	2	0	0	0.00
29	2	2	0	0	0.00
30	2	2	0	0	0.00
31	2	2	0	0	0.00
32	2	2	0	0	0.00
33	2	2	0	0	0.00
34	10	2	0	0	0.35
35	10	2	0	0	0.35
36	10	2	0	0	0.35

INFEXP: Infiltration Exponent
INFILD: Infiltration ratio (maximum to mean)
DEEPFR: Fraction of groundwater to deep aquifer or inactive storage
BASETP: Base flow (from groundwater) Evapotranspiration fraction
AGWETP: Active Groundwater Evapotranspiration fraction

Table 4. WWHM3 HSPF Pervious Parameter Values – Part III

PERLND No.	CEPSC	UZSN	NSUR	INTFW	IRC	LZETP
1	0.20	0.50	0.35	0	0.7	0.70
2	0.20	0.50	0.35	0	0.7	0.70
3	0.20	0.50	0.35	0	0.7	0.70
4	0.15	0.50	0.30	0	0.7	0.40
5	0.15	0.50	0.30	0	0.7	0.40
6	0.15	0.50	0.30	0	0.7	0.40
7	0.10	0.50	0.25	0	0.7	0.25
8	0.10	0.50	0.25	0	0.7	0.25
9	0.10	0.50	0.25	0	0.7	0.25
10	0.20	0.50	0.35	6	0.5	0.70
11	0.20	0.50	0.35	6	0.5	0.70
12	0.20	0.30	0.35	6	0.3	0.70
13	0.15	0.40	0.30	6	0.5	0.40
14	0.15	0.40	0.30	6	0.5	0.40
15	0.15	0.25	0.30	6	0.3	0.40
16	0.10	0.25	0.25	6	0.5	0.25
17	0.10	0.25	0.25	6	0.5	0.25
18	0.10	0.15	0.25	6	0.3	0.25
19	0.20	3.00	0.50	1	0.7	0.80
20	0.20	3.00	0.50	1	0.7	0.80
21	0.20	3.00	0.50	1	0.7	0.80
22	0.15	3.00	0.50	1	0.7	0.60
23	0.15	3.00	0.50	1	0.7	0.60
24	0.15	3.00	0.50	1	0.7	0.60
25	0.10	3.00	0.50	1	0.7	0.40
26	0.10	3.00	0.50	1	0.7	0.40
27	0.10	3.00	0.50	1	0.7	0.40
28	0.10	0.25	0.25	6	0.5	0.25
29	0.10	0.25	0.25	6	0.5	0.25
30	0.10	0.15	0.25	6	0.3	0.25
31	0.10	0.50	0.25	0	0.7	0.25
32	0.10	0.50	0.25	0	0.7	0.25
33	0.10	0.50	0.25	0	0.7	0.25
34	0.10	3.00	0.50	1	0.7	0.40
35	0.10	3.00	0.50	1	0.7	0.40
36	0.10	3.00	0.50	1	0.7	0.40

CEPSC: Interception storage (inches)
UZSN: Upper Zone Storage Nominal (inches)
NSUR: Surface roughness (Manning's n)
INTFW: Interflow index
IRC: Interflow Recession Constant (per day)
LZETP: Lower Zone Evapotranspiration fraction

Table 5. WWHM3 HSPF Pervious Parameter Values – Part IV

PERLND No.	MELEV	BELV	GWDATM	PCW	PGW	UPGW
1	400	0	0	0.35	0.38	0.45
2	400	0	0	0.35	0.38	0.45
3	400	0	0	0.35	0.38	0.45
4	400	0	0	0.33	0.35	0.42
5	400	0	0	0.33	0.35	0.42
6	400	0	0	0.33	0.35	0.42
7	400	0	0	0.31	0.33	0.40
8	400	0	0	0.31	0.33	0.40
9	400	0	0	0.31	0.33	0.40
10	400	0	0	0.20	0.23	0.28
11	400	0	0	0.20	0.23	0.28
12	400	0	0	0.20	0.23	0.28
13	400	0	0	0.18	0.20	0.25
14	400	0	0	0.18	0.20	0.25
15	400	0	0	0.18	0.20	0.25
16	400	0	0	0.15	0.17	0.20
17	400	0	0	0.15	0.17	0.20
18	400	0	0	0.15	0.17	0.20
19	400	0	0	0.17	0.20	0.25
20	400	0	0	0.17	0.20	0.25
21	400	0	0	0.17	0.20	0.25
22	400	0	0	0.15	0.17	0.22
23	400	0	0	0.15	0.17	0.22
24	400	0	0	0.15	0.17	0.22
25	400	0	0	0.12	0.15	0.18
26	400	0	0	0.12	0.15	0.18
27	400	0	0	0.12	0.15	0.18
28	400	0	0	0.15	0.17	0.20
29	400	0	0	0.15	0.17	0.20
30	400	0	0	0.15	0.17	0.20
31	400	0	0	0.31	0.33	0.40
32	400	0	0	0.31	0.33	0.40
33	400	0	0	0.31	0.33	0.40
34	400	0	0	0.12	0.15	0.18
35	400	0	0	0.12	0.15	0.18
36	400	0	0	0.12	0.15	0.18

MELEV: Mean surface elevation of the land segment (feet)
BELV: Base elevation for active groundwater (feet)
GWDATM: Datum for the groundwater elevation (feet)
PCW: Cohesion Water Porosity (fraction)
PGW: Gravitational Water Porosity (fraction)
UPGW: Upper Gravitational Water porosity (fraction)
A description of these parameters is in Appendix C.

Table 6. WWHM3 HSPF Pervious Parameter Values – Part V

PERLND No.	STABNO	SRRC	SREXP	IFWSC	DELTA	UELFAC	LELFAC
1	1	0.1	0	4	0.2	4	2.5
2	1	0.1	0	4	0.2	4	2.5
3	1	0.1	0	4	0.2	4	2.5
4	1	0.1	0	4	0.2	4	2.5
5	1	0.1	0	4	0.2	4	2.5
6	1	0.1	0	4	0.2	4	2.5
7	1	0.1	0	4	0.2	4	2.5
8	1	0.1	0	4	0.2	4	2.5
9	1	0.1	0	4	0.2	4	2.5
10	1	0.1	0	4	0.2	4	2.5
11	1	0.1	0	4	0.2	4	2.5
12	1	0.1	0	4	0.2	4	2.5
13	1	0.1	0	4	0.2	4	2.5
14	1	0.1	0	4	0.2	4	2.5
15	1	0.1	0	4	0.2	4	2.5
16	1	0.1	0	4	0.2	4	2.5
17	1	0.1	0	4	0.2	4	2.5
18	1	0.1	0	4	0.2	4	2.5
19	1	0.1	0	4	0.2	4	2.5
20	1	0.1	0	4	0.2	4	2.5
21	1	0.1	0	4	0.2	4	2.5
22	1	0.1	0	4	0.2	4	2.5
23	1	0.1	0	4	0.2	4	2.5
24	1	0.1	0	4	0.2	4	2.5
25	1	0.1	0	4	0.2	4	2.5
26	1	0.1	0	4	0.2	4	2.5
27	1	0.1	0	4	0.2	4	2.5
28	1	0.1	0	4	0.2	4	2.5
29	1	0.1	0	4	0.2	4	2.5
30	1	0.1	0	4	0.2	4	2.5
31	1	0.1	0	4	0.2	4	2.5
32	1	0.1	0	4	0.2	4	2.5
33	1	0.1	0	4	0.2	4	2.5
34	1	0.1	0	4	0.2	4	2.5
35	1	0.1	0	4	0.2	4	2.5
36	1	0.1	0	4	0.2	4	2.5

STABNO: User's number for the FTABLE in the FTABLES block which contains the outflow properties from the surface storage
SRRC: Surface Runoff Recession Constant (per hour)
SREXP: Surface Runoff Exponent
IFWSC: Maximum Interflow Storage Capacity when the groundwater elevation is greater than the upper influence elevation (inches)

DELTA: groundwater tolerance level used to determine transition between regions when high water table conditions are being simulated
UELFAC: multiplier on UZSN which gives the upper zone capacity
LELFAC: multiplier on LZSN which gives the lower zone capacity

The selection of the Table 5 and Table 6 default parameter values is based on limited application of these parameters in Western Washington by the staff of Clear Creek Solutions, Inc.. The parameter values should be used with caution and only after consultation with the Department of Ecology. Different values should only be selected following detailed local soil analysis, a thorough understanding of the parameters and algorithms, and consultation with the Department of Ecology.

A description of the Table 5 and Table 6 parameters and algorithms is in a separate document titled "WWHM3 Description of HSPF High Groundwater Parameters" available from the Washington State Department of Ecology.

Table 7. WWHM3 HSPF Pervious Parameter Values – Part VI

PERLND No.	CEPS	SURS	UZS	IFWS	LZS	AGWS	GWVS
1	0	0	0	0	3.0	1	0
2	0	0	0	0	3.0	1	0
3	0	0	0	0	3.0	1	0
4	0	0	0	0	3.0	1	0
5	0	0	0	0	3.0	1	0
6	0	0	0	0	3.0	1	0
7	0	0	0	0	3.0	1	0
8	0	0	0	0	3.0	1	0
9	0	0	0	0	3.0	1	0
10	0	0	0	0	2.5	1	0
11	0	0	0	0	2.5	1	0
12	0	0	0	0	2.5	1	0
13	0	0	0	0	2.5	1	0
14	0	0	0	0	2.5	1	0
15	0	0	0	0	2.5	1	0
16	0	0	0	0	2.5	1	0
17	0	0	0	0	2.5	1	0
18	0	0	0	0	2.5	1	0
19	0	0	0	0	4.2	1	0
20	0	0	0	0	4.2	1	0
21	0	0	0	0	4.2	1	0
22	0	0	0	0	4.2	1	0
23	0	0	0	0	4.2	1	0
24	0	0	0	0	4.2	1	0
25	0	0	0	0	4.2	1	0
26	0	0	0	0	4.2	1	0
27	0	0	0	0	4.2	1	0
28	0	0	0	0	2.5	1	0
29	0	0	0	0	2.5	1	0
30	0	0	0	0	2.5	1	0
31	0	0	0	0	3.0	1	0
32	0	0	0	0	3.0	1	0
33	0	0	0	0	3.0	1	0
34	0	0	0	0	4.2	1	0
35	0	0	0	0	4.2	1	0
36	0	0	0	0	4.2	1	0

CEPS: Initial interception storage (inches)
SURS: Initial surface runoff (inches)
UZS: Initial Upper Zone Storage (inches)
IFWS: Initial interflow (inches)
LZS: Initial Lower Zone Storage (inches)
AGWS: Initial Active Groundwater storage (inches)
GWVS: Initial Groundwater Vertical Slope (feet/feet)

APPENDIX B: DEFAULT WWHM3 HSPF IMPERVIOUS PARAMETER VALUES

The default WWHM3 HSPF impervious parameter values are found in the WWHM3 file defaultpers.uci.

The default WWHM3 HSPF impervious parameter values are based on the USGS report: Dinicola, R.S. 1990. Characterization and Simulation of Rainfall-Runoff Relations for Headwater Basins in Western King and Snohomish Counties, Washington. Water-Resources Investigations Report 89-4052. U.S. Geological Survey. Tacoma, WA.

For some parameters the default WWHM3 HSPF impervious parameter values have been modified from the values listed in the USGS report. These modifications are based on the professional judgment and experience of Clear Creek Solutions staff in modeling Western Washington watersheds with HSPF.

HSPF parameter documentation is found in the document:
Bicknell, B.R., J.C. Imhoff, J.L. Kittle Jr, T.H. Jobes, and A.S. Donigian Jr. 2001. Hydrological Simulation Program – Fortran, User's Manual for Version 12. AQUA TERRA Consultants. Mountain View, CA.

Table 1. WWHM3 Impervious Land Types

IMPLND No.	Impervious Surface	Slope
1	Roads	Flat
2	Roads	Moderate
3	Roads	Steep
4	Roofs	Flat
5	Driveways	Flat
6	Driveways	Moderate
7	Driveways	Steep
8	Sidewalks	Flat
9	Sidewalks	Moderate
10	Sidewalks	Steep
11	Parking	Flat
12	Parking	Moderate
13	Parking	Steep
14	Pond	Flat

Table 2. WWHM3 HSPF Impervious Parameter Values – Part I

IMPLND No.	LSUR	SLSUR	NSUR	RETSC
1	400	0.01	0.10	0.10
2	400	0.05	0.10	0.08
3	400	0.10	0.10	0.05
4	400	0.01	0.10	0.10
5	400	0.01	0.10	0.10
6	400	0.05	0.10	0.08
7	400	0.10	0.10	0.05
8	400	0.01	0.10	0.10
9	400	0.05	0.10	0.08
10	400	0.10	0.10	0.05
11	400	0.01	0.10	0.10
12	400	0.05	0.10	0.08
13	400	0.10	0.10	0.05
14	400	0.01	0.10	0.10

LSUR: Length of surface flow path (feet) for impervious area
SLSUR: Slope of surface flow path (feet/feet) for impervious area
NSUR: Surface roughness (Manning’s n) for impervious area
RETSC: Surface retention storage (inches) for impervious area

Table 3. WWHM3 HSPF Impervious Parameter Values – Part II

IMPLND No.	RETS	SURS
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0

RETSC: Initial surface retention storage (inches) for impervious area
SURS: Initial surface runoff (inches) for impervious area