drainage patterns. Constructional landforms typical of urbanized watersheds, such as levees, tend to disconnect streams from their floodplains.

Changes in Geomorphology from Urbanization

Changes to channel morphology are among the most common and readily visible effects of urban development on natural stream systems (Booth and Henshaw, 2001). The actions of deforestation, channelization, and paving of the uplands can produce tremendous changes in the delivery of water and sediment into the channel network. In channel reaches that are alluvial, the responses are commonly rapid and often dramatic. Channels widen and deepen, and in some cases may incise many meters below the original level of their beds. Alternatively, channels may fill with sediment derived from farther upstream to produce a braided form where a single-thread channel previously existed.

The clearest single determinant of urban channel change is the alteration of the hydrologic response of an urban watershed, notably the increase in stream-flow discharges. Increases in runoff mobilize sediment both on the land surface and within the stream channel. Because transport capacity increases nonlinearly with flow velocity (Vogel et al., 2003), much greater transport will occur in higher flow events. However, the low frequency of these events may result in decreasing cumulative sediment transport during the highest flows, as described by standard magnitude and frequency analysis (Wolman and Miller, 1960), such that the maximum time-integrated sediment transport occurs at moderate flows (e.g., bankfull stage in streams in the eastern United States).

If the increase in sediment transport caused by the shift in the runoff regime is not matched by the sediment supply, channel bed entrenchment and bank erosion and collapse lead to a deeper, wider channel form. Increases in channel dimensions caused by increased discharges have been observed in numerous studies, including Hammer (1972), Hollis and Luckett (1976), Morisawa and LaFlure (1982), Neller (1988), Whitlow and Gregory (1989), Moscrip and Montgomery (1997), and Booth and Jackson (1997). MacRae (1997), reporting on other studies, found that channel cross-sectional areas began to enlarge after about 20 to 25 percent of the watershed was developed, commonly corresponding to about 5 percent impervious cover. When the watersheds were completely developed, the channel enlargements were about 5 to 7 times the original cross-sectional areas. Channel widening can occur for several decades before a new equilibrium is established between the new cross-section and the new discharges.

Construction results in a large—but normally temporary—increase in sediment load to aquatic systems (e.g., Wolman and Schick, 1967). Indeed, erosion and sediment transport rates can reach up to more than 200 Mg/ha/yr on construction sites, which is well in excess of typical rates from agricultural land (e.g., Wolman and Schick, 1967; Dunne and Leopold, 1978); rates from undisturbed and well-vegetated catchments are negligible (e.g., <<1 Mg/ha/yr). The increased sediment loads from construction exert an opposing tendency to channel erosion and probably explain much of the channel narrowing or shallowing that is sometimes reported (e.g., Leopold, 1973; Nanson and Young, 1981; Ebisemiju, 1989; Odemerho, 1992).

Additional sediment is commonly introduced into the channel network by the erosion of the streambank and bed itself. Indeed, this source can become the largest single fraction of the sediment load in an urbanizing watershed (Trimble, 1997). For example, Nelson and Booth (2002) reported on sediment sources in the Issaquah Creek watershed, an urbanizing, mixed-use watershed in the Pacific Northwest. Human activity in the watershed, particularly urban development, has caused an increase of nearly 50 percent in the annual sediment yield, now estimated to be 44 tons/km^2/yr^1. The main sources of sediment in the watershed are landslides (50 percent), channel-bank erosion (20 percent), and stormwater discharges (15 percent).

The higher flow volumes and peak discharge caused by urbanization also tend to preferentially remove fine-grained sediment, leaving a lag of coarser bed material (armoring) or removing alluvial material entirely and eroding into the geologic substrate (Figure 3-24). The geomorphic outcome of these changes is a mix of erosional enlargement of some stream reaches, significant sedimentation in others, and potential head-ward downcutting of tributaries as discharge levels from small catchments increase. The collective effects of these processes have been described by Walsh et al. (2005) as "Urban Stream Syndrome," which includes not only the visible alteration of the physical form of the channel but also the consequent deterioration of stream biogeochemical function and aquatic trophic structures.

Other changes also accompany these geomorphic changes. Episodic inundation of the floodplain during floods may be reduced in magnitude and frequency, depending on the increases in peak flow relative to the deepening and resultant increase in flow capacity of the channel. Where deeply entrenched, this channel morphology will lower the groundwater level adjacent to the channel. The effectiveness of riparian areas in filtering or removing solutes is thus reduced because subsurface water may reach the channel only by flowpaths now well below the organic-rich upper soil horizons. Removal of fine-grained stream-bottom sediment, or erosion down to bedrock, may substantially lower the exchange of stream water with the surrounding groundwater of the hyporheic zone.

FIGURE 3-24 Example of an urban stream that has eroded entirely through its alluvium to expose the underlying consolidated geologic stratum below (Thornton Creek, Seattle, Washington).

In addition to these indirect effects on the physical form of the stream channel, urbanization also commonly modifies streams directly to improve drainage, applying channel straightening and lining to reduce friction, increase flow capacity, and stabilize channel position (Figure 3-25). The enlarged and often lined and straightened stream-channel cross section reduces the complexity of the bed and the contact between the stream and floodplain, and increases transport efficiency of sediment and solutes to receiving waterbodies. Enhanced sedimentation of receiving waterbodies, in turn, reduces water clarity, decreases depth, and buries the benthic environment.

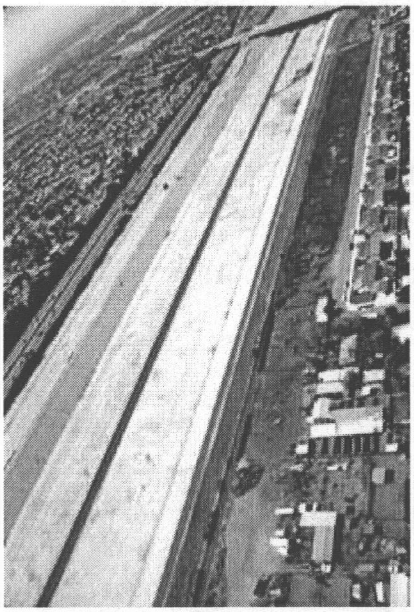


FIGURE 3-25 Example of a channelized urban stream for maximized flood conveyance and geomorphic stability (Los Angeles River, California). SOURCE: Reprinted, with permission, from Water Resources Research. Copyright by the American Geophysical Union.

POLLUTANT LOADING IN STORMWATER

Hydrologic flowpaths influence the production of particulate and dissolved substances on the land surface during storms, as well as their delivery to the stream-channel network. Natural watersheds typically develop a sequence of ecosystem types along hydrologic flowpaths that utilize available limiting resources, thereby reducing their export farther downslope or downstream, such that in-stream concentrations of these nutrients are low. As a watershed shifts from having mostly natural pervious surfaces to having heavily disturbed soils, new impervious surfaces, and activities characteristic of urbanization, the runoff quality shifts from relatively lower to higher concentrations of pollutants. Anthropogenic activities that can increase runoff pollutant concentrations in urban watersheds include application of chemicals for fertilization and pest control; leaching and corrosion of pollutants from exposed materials; exhaust emissions, leaks from, and wear of vehicles; atmospheric deposition of pollutants; and inappropriate discharges of wastes.

Most lands in the United States that have been developed were originally grasslands, prairies, or forest. About 40 percent of today's developed land went through an agricultural phase (cropland or pastureland) before becoming urbanized, while more than half of today's developed land area has been a direct conversion of natural covers (USDA, 2000). Agricultural land can produce stormwater runoff with high pollutant concentrations via soil erosion, the introduction of chemicals (fertilizers, pesticides, and herbicides), animal operations that are major sources of bacteria in runoff, and forestry operations. Indeed, urban stormwater may actually have slightly lower pollutant concentrations than other nonpoint sources of pollution, especially for sediment and nutrients. The key difference is that urban watersheds produce a much larger annual volume of runoff waters, such that the mass of pollutants discharged is often greater following urbanization. Some of the complex land-use–pollutant loading relationships are evident in Box 3-7, which shows the measured annual mass loads of nitrogen and phosphorus in four small watersheds of different land use monitored as part of the Baltimore Long-Term Ecological Research program. Depending on the nutrient and the year, the agricultural and urban watersheds had a higher nutrient export rate than the forested subwatershed.

BOX 3-7
Comparison of Nitrogen and Phosphorus Export from Watersheds with Different Land Uses

Land use is a significant influence on nutrient export as controlled by impervious area, sanitary infrastructure, fertilizer application, and other determinants of input, retention, and stormwater transport. Tables 3-2A and 3-2B compare dissolved nitrate, total nitrogen, phosphate, and total phosphorus loads exported from forest catchments with catchments in different developed land uses studied by the Baltimore Ecosystem Study (Groffman et al., 2004). Loads were computed with the Fluxmaster system (Schwarz et al., 2006) from weekly samples taken at outlet gauges. In these sites in Baltimore County, the forested catchment, Pond Branch, has nitrogen loads one to two orders of magnitude lower than the developed catchments. Baisman Run, with one-third of the catchment in low-density, septic-served suburban land use, has nitrogen export exceeding Dead Run, an older, dense urban catchment. In this case, nutrient load does not follow the direct variation of impervious area because of the switch to septic systems and greater fertilizer use in lower density areas. However, Figure 3-26 shows that as impervious area increases, a much greater proportion of the total nitrogen load is discharged in less frequent, higher runoff events (Shields et al., 2008), reducing the potential to decrease loads by on-site SCMs. Total phosphorus loads were similarly as low (0.05–0.6 kg P/ha/yr) as nitrogen in the Pond Branch catchment (forest) over the 2000–2004 time period, and one to two orders of magnitude lower compared to agricultural and residential catchments.

It should be noted that specific areal loading rates, even in undeveloped catchments, can vary significantly depending on rates of atmospheric deposition, disturbance, and climate conditions. The hydrologic connectivity of nonpoint pollutant source areas to receiving waterbodies is also a critical control on loading in developed catchments (Nadeau and Rains, 2007) and is dependent on both properties of the pollutant as well as the catchment hydrology. For example, total nitrogen was high in both the agricultural and low-density suburban sites. Total phosphorus, on the other hand, was high in the Baltimore Ecosystem Study agricultural catchment, but close to the concentration of the forest site in the low-density suburban site serviced by septic systems. This is because septic systems tend to retain phosphorus, while septic wastewater nitrogen is typically nitrified in the unsaturated zone below a spreading field and efficiently transported in the groundwater to nearby streams.

continues next page

BOX 3-7 Continued

TABLE 3-2A Dissolved Nitrate and Total Nitrogen Export Rates from Forest and Developed Land-Use Catchments in the Baltimore Ecosystem Study

Catchment	Land Use	Nitrate (kg N/ha/yr)			Total N (kg N/ha/yr)		
		2000	2001	2002	2000	2001	2002
Pond Branch	Forest	0.11	0.08	0.04	.47	.37	0.17
McDonogh	Agriculture	17.6	12.9	4.3	20.5	14.5	4.5
Baisman Run	Mixed Forest and Suburban	7.2	3.8	1.5	8.2	4.2	1.7
Dead Run	Urban	3.0	2.9	2.9	5.6	5.3	4.2

TABLE 3-2B Dissolved Phosphate and Total Phosphorus Export Rates from Forest and Developed Land-Use Catchments in the Baltimore Ecosystem Study

Catchment	Land Use	Phosphate (kg P/ha/yr)			Total P (kg P/ha/yr)		
		2000	2001	2002	2000	2001	2002
Pond Branch	Forest	0.009	0.007	0.003	0.02	0.014	0.006
McDonogh	Agriculture	0.12	0.080	0.022	0.22	0.14	0.043
Baisman Run	Mixed Forest and Suburban	0.009	0.005	0.002	0.02	0.011	0.004
Dead Run	Urban	0.039	0.037	0.03	0.10	0.10	0.08

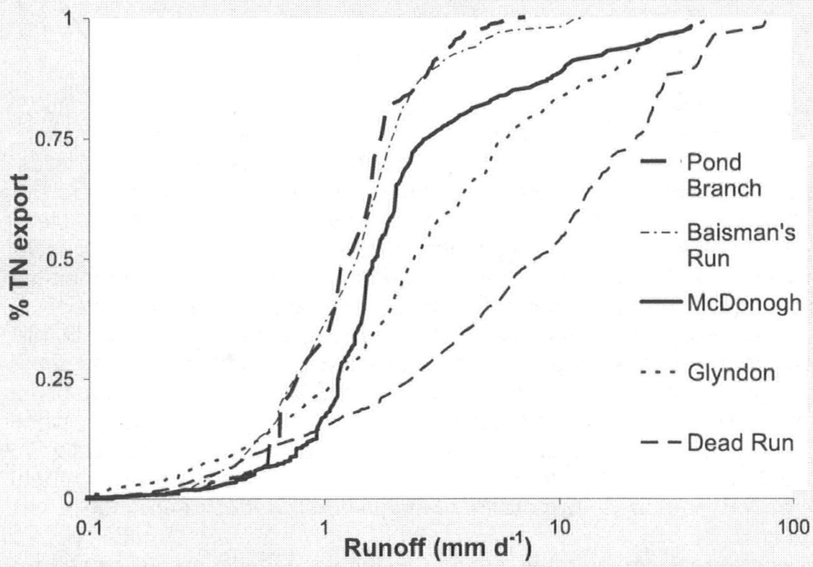


FIGURE 3-26 Cumulative transport of total nitrogen at increasing flow levels from catchments in Baltimore City and County including dominantly forest (Pond Branch), low-density development on septic systems and forest (Baisman Run), agricultural (McDonogh), medium-density suburban development on separate sewers (Glyndon), and higher-density residential, commercial, and highway land cover (Dead Run). SOURCE: Reprinted, with permission, from Shields et al. (2008). Copyright 2008 by the American Geophysical Union.

Table 3-3 summarizes the comparative importance of urban land-use types in generating pollutants of concerns that can impact receiving waters (Burton and Pitt, 2002). This summary is highly qualitative and may vary depending on the site-specific conditions, regional climate, activities being conducted in each land use, and development characteristics. It should be noted that the rankings in Table 3-3 are relative to one another and classified on a per-unit-area basis. Furthermore, this table shows the parameters for each land-use category, such that the effects for a community at large would be dependent on the areas of each land use shown. Thus, although residential land use is shown to be a relatively smaller source of many pollutants, it is the largest fraction of land use in most communities, typically making it the largest stormwater source on a mass pollutant discharge basis. Similarly, freeway, industrial, and commercial areas can be very significant sources of many stormwater problems, and their discharge significance is usually much greater than their land area indicates. Construction sites are usually the overwhelming source of sediment in urban areas, even though they make up very small areas of most communities. A later table (Table 3-4) presents observed stormwater discharge concentrations for selected constituents for different land uses.

The following section describes stormwater characteristics associated with urbanized conditions. At any given time, parts of an urban area will be under construction, which is the source of large sediment losses, flow path disruptions, increased runoff quantities, and some chemical contamination. Depending on the time frame of development, increased stormwater pollutant discharges associated with construction activities may last for several years until land covers are stabilized. After construction has been completed, the characteristics of urban runoff are controlled largely by the increase in volume and the washoff of pollutants from impervious

TABLE 3-3 Relative Sources of Parameters of Concern for Different Land Uses in Urban Areas

Problem Parameter	Residential	Commercial	Industrial	Freeway	Construction
High flow rates (energy)	Low	High	Moderate	High	Moderate
Large runoff volumes	Low	High	Moderate	High	Moderate
Debris (floatables and gross solids)	High	High	Low	Moderate	High
Sediment	Low	Moderate	Low	Low	Very high
Inappropriate discharges (mostly sewage and cleaning wastes)	Moderate	High	Moderate	Low	Low
Microorganisms	High	Moderate	Moderate	Low	Low
Toxicants (heavy metals and organics)	Low	Moderate	High	High	Moderate
Nutrients (eutrophication)	Moderate	Moderate	Low	Low	Moderate
Organic debris (SOD and DO)	High	Low	Low	Low	Moderate
Heat (elevated water temperature)	Moderate	High	Moderate	High	Low

NOTE: SOD, sediment oxygen demand; DO, dissolved oxygen.
SOURCE: Summarized from Burton and Pitt (2002), Pitt et al. (2008), and CWP and Pitt (2008).

surfaces. Stormwater in this phase is associated with increases in discharges of most pollutants, but with less sediment washoff than from construction and likely less sediment and nutrient discharges compared to any pre-urbanization agricultural operations (although increased channel erosion may increase the mass of sediment delivered in this phase; Pitt et al., 2007). A third significant urban land use is industrial activity. As described later, industrial site stormwater discharges are highly variable, but often greater than other land uses.

Construction Site Erosion Characteristics

Problems associated with construction site runoff have been known for many years. More than 25 years ago, Willett (1980) estimated that approximately 5 billion tons of sediment reached U.S. surface waters annually, of which 30 percent was generated by natural processes and 70 percent by human activities. Half of this 70 percent was attributed to eroding croplands. Although construction occurred on only about 0.007 percent of U.S. land in the 1970s, it accounted for approximately 10 percent of the sediment load to all U.S. surface waters and equaled the combined sediment contributions of forestry, mining, industrial, and commercial land uses (Willett, 1980).

Construction accounts for a much greater proportion of the sediment load in urban areas than it does in the nation as a whole. This is because construction sites have extremely high erosion rates and because urban construction sites are efficiently drained by stormwater drainage systems installed early during the construction activities. Construction site erosion losses vary greatly throughout the nation, depending on local rain, soil, topographic, and management conditions. As an example, the Birmingham, Alabama, area may have some of the highest erosion rates in the United States because of its combination of very high-energy rains, moderately to severely erosive soils, and steep slopes (Pitt et al., 2007). The typically high erosion rates mean that even a small construction project may have a significant detrimental effect on local waterbodies.

Extensive evaluations of urban construction site runoff problems have been conducted in Wisconsin for many years. Data from the highly urbanized Menomonee River watershed in southeastern Wisconsin indicate that construction sites have much greater potentials for generating sediment and phosphorus than do other land uses (Chesters et al., 1979). For example, construction sites can generate approximately 8 times more sediment and 18 times more phosphorus than industrial sites (the land use that contributes the second highest amount of these pollutants) and 25 times more sediment and phosphorus than row crops. In fact, construction sites contributed more sediment and phosphorus to the Menomonee River than any other land use, although in 1979, construction comprised only 3.3 percent of the watershed's total land area. During this early study, construction sites were found to contribute about 50 percent of the suspended sediment and total phosphorus loading at the river mouth (Novotny and Chesters, 1981).

Similar conclusions were reported by the Southeastern Wisconsin Regional Planning Commission (SEWRPC) in a 1978 modeling study of the relative pollutant contributions of 17 categories of point and nonpoint pollution sources to 14 watersheds in the southeast Wisconsin regional planning area (SEWRPC, 1978). This study revealed construction as the first or second largest contributor of sediment and phosphorus in 12 of the 14 watersheds. Although construction occupied only 2 percent of the region's total land area in 1978, it contributed approximately 36 percent of the sediment and 28 percent of the total phosphorus load to inland waters, making construction the region's second largest source of these two pollutants. The largest source of sediment was estimated to be cropland; livestock operations were estimated to be the largest source of phosphorus. By comparison, cropland comprised 72 percent of the region's land area and contributed about 45 percent of the sediment and only 11 percent of the phosphorus to regional watersheds. When looking at the Milwaukee River watershed as a whole, construction is a major sediment contributor, even though the amount of land under active construction is very low. Construction areas were estimated to contribute about 53 percent of the total sediment discharged by the Milwaukee River in 1985 (total sediment load of 12,500 lb/yr), while croplands contributed 25 percent, streambank erosion contributed 13 percent, and urban runoff contributed 8 percent.

Line and White (2007) recently investigated runoff characteristics from two similar drainage areas in the Piedmont region of North Carolina. One of the drainage areas was being developed as part of a large residential subdivision during the course of the study, while the other remained forested or in agricultural fields. Runoff volume was 68 percent greater for the developing compared with the undeveloped area, and baseflow as a percentage of overall discharge was approximately zero compared with 25 percent for the undeveloped area. Overall annual export of sediment was 95 percent greater for the developing area, while export of nitrogen and phosphorus forms was 66 to 88 percent greater for the developing area.

The biological stream impact of construction site runoff can be severe. For example, Hunt and Grow (2001) describe a field study conducted to determine the impact to a stream from a poorly controlled construction site, with impact being measured via fish electroshocking and using the Qualitative Habitat Evaluation Index. The 33-acre construction site consisted of severely eroded silt and clay loam subsoil and was located within the Turkey Creek drainage, Scioto County, Ohio. The number of fish species declined (from 26 to 19) and the number of fish found decreased (from 525 to 230) when comparing upstream unimpacted reaches to areas below the heavily eroding site. The Index of Biotic Integrity and the Modified Index of Well-Being, common fisheries indexes for stream quality, were reduced from 46 to 32 and 8.3 to 6.3, respectively. Upstream of the area of impact, Turkey Creek had the highest water quality designation available, but fell to the lowest water quality designation in the area of the construction activity. Water quality sampling conducted at upstream and downstream sites verified that the decline in fish diversity was not due to chemical affects alone.

Municipal Stormwater Characteristics

The suite of stormwater pollutants generated by municipal areas is expected to be much more diverse than construction sites because of the greater variety of land uses and pollutant source areas found within a typical city. Many studies have investigated stormwater quality, with the U.S. Environmental Protection Agency's (EPA's) NURP (EPA, 1983) being the best known and earliest effort to collect and summarize these data. Unfortunately, NURP was limited in that it did not represent all areas of the United States or all important land uses. More recently, the National Stormwater Quality Database (NSQD) (CWP and Pitt, 2008; Pitt et al., 2008 for version 3) has been compiling data from the EPA's NPDES stormwater permit program for larger Phase I municipal separate storm sewer system (MS4) communities. As a condition of their Phase I permits, municipalities were required to establish a monitoring program to characterize their local stormwater quality for their most important land uses discharging to the MS4. Although only a few samples from a few locations were required to be monitored each year in each community, the many years of sampling and large number of communities has produced a database containing runoff quality information for nearly 8,000 individual storm events over a wide range of urban land uses. The NSQD makes it possible to statistically compare runoff from different land uses for different areas of the country.

A number of land uses are represented in MS4 permits and also the database, including industrial stormwater discharges to an MS4. However, there is no separate compilation of quantitative mass emissions from specific industrial stormwater sources that may have been collected under industrial permit monitoring efforts. The observations in the NSQD were all obtained at outfall locations and do not include snowmelt or construction erosion sources. The most recent version of the NSQD contains stormwater data from about one-fourth of the total number of communities that participated in the Phase I NPDES stormwater permit monitoring activities. The database is located at http://unix.eng.ua.edu/~rpitt/Research/ms4/mainms4.shtml.

Table 3-4 is a summary of *some* of the stormwater data included in NSQD version 3, while Figure 3-27 shows selected plots of these data. The table describes the total number of observations, the percentage of observations above the detection limits, the median, and coefficients of variation for a few of the major constituents for residential, commercial, industrial, institutional, freeway, and open-space land-use categories, although relatively few data are available for institutional and open-space areas. It should be noted that even if there are significant differences in the median concentrations by the land uses, the range of the concentrations within single land uses can still be quite large. Furthermore, plots like Figure 3-27 do not capture the large variability in data points observed at an individual site.

There are many factors that can be considered when examining the quality of stormwater, including land use, geographical region, and season. The following is a narrative summary of the entire database and may not reflect information in Table 3-4 and Figure 3-29, which show only subsets of the data. First, statistical analyses of variance on the NSQD found significant differences among land-use categories for all of the conventional constituents, except for dissolved oxygen. (Turbidity, total solids, total coliforms, and total *E. coli* did not have enough samples in each group to evaluate land-use differences.) Freeway sites were found to be significant sources of several pollutants. For example, the highest TSS, COD, and oil and grease concentrations (but not necessarily the highest *median* concentrations) were reported for freeways. The median ammonia concentration in freeway stormwater is almost three times the median concentration observed in residential and open-space land uses, while freeways have the lowest orthophosphate and nitrite–nitrate concentrations—half of the concentration levels that were observed in industrial land uses.

In almost all cases the median metal concentrations at the industrial areas were about three times the median concentrations observed in open-space and residential areas. The highest lead and zinc concentrations (but not necessarily the highest *median* concentrations) were found in industrial land uses. Lower concentrations of TDS, five-day biological oxygen demand (BOD_5), and fecal coliforms were observed in industrial land-use areas. By contrast, the highest concentrations of dissolved and total phosphorus were associated with residential land uses. Fecal coliform concentrations are also relatively high for residential and mixed residential land uses. Open-space land-use areas show consistently low concentrations for the constituents examined. There was no significant difference noted for total nitrogen among any of the land uses monitored.

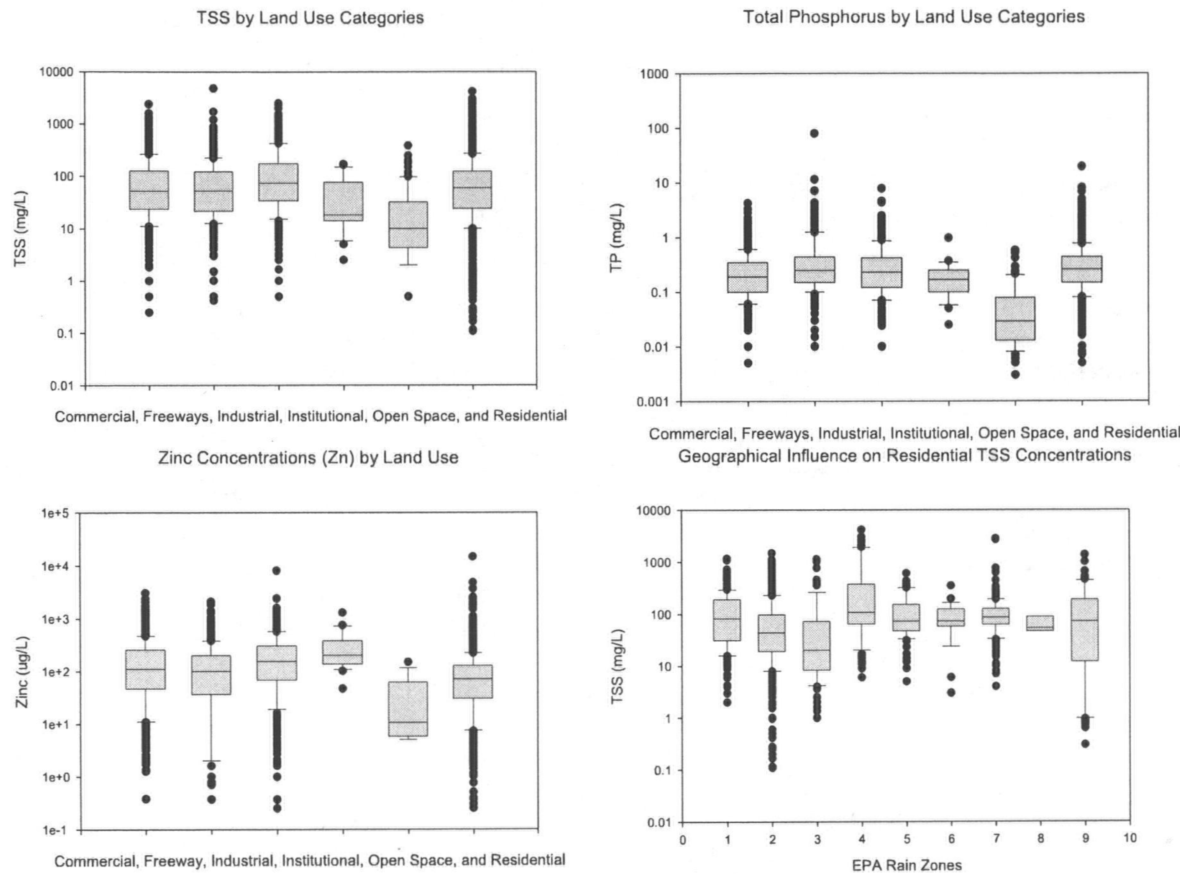


FIGURE 3-27 Grouped box and whisker plots of data from the NSQD. The median values are indicated with the horizontal line in the center of the box, while the ends of the box represent the 25th and 75th percentile values. The whickers extend to the 5th and 95th percentile values, and values outside of these extremes are indicated with separate dots. These groups were statistically analyzed and were found to have at least one group that is significantly different from the other groups. The ranges of the values in each group are large, but a very large number of data points is available for each group. The grouping of the data into these categories helps explain much of the total variability observed, and the large number of samples in each category allows suitable statistical tests to be made. Many detailed analyses are presented at the NSQD website (Maestre and Pitt, 2005).

TABLE 3-4 Summary of Selected Stormwater Quality Data Included in NSQD, Version 3.0

	TSS (mg/L)	COD (mg/L)	Fecal Colif. (mpn/100 mL)	Nitrogen, Total Kjeldahl (mg/L)	Phosphorus, Total (mg/L)	Cu, Total (µg/L)	Pb, Total (µg/L)	Zn, Total (µg/L)
All Areas Combined (8,139)								
Coefficient of variation (COV)	2.2	1.1	5.0	1.2	2.8	2.1	2.0	3.3
Median	62.0	53.0	4300	1.3	0.2	15.0	14.0	90.0
Number of samples	6780	5070	2154	6156	7425	5165	4694	6184
% samples above detection	99	99	91	97	97	88	78	98
All Residential Areas Combined (2,586)								
COV	2.0	1.0	5.7	1.2	1.6	1.9	2.1	3.3
Median	59.0	50.0	4200	1.2	0.3	12.0	6.0	70.0
Number of samples	2167	1473	505	2026	2286	1640	1279	1912
% samples above detection	99	99	89	98	98	88	77	97
All Commercial Areas Combined (916)								
COV	1.7	1.0	3.0	0.9	1.2	1.4	1.7	1.4
Median	55.0	63.0	3000	1.3	0.2	17.9	15.0	110.0
Number of samples	843	640	270	726	920	753	605	839
% samples above detection	97	98	89	98	95	85	79	99
All Industrial Areas Combined (719)								
COV	1.7	1.3	6.1	1.1	1.4	2.1	2.0	1.7
Median	73.0	59.0	2850	1.4	0.2	19.0	20.0	156.2
Number of samples	594	474	317	560	605	536	550	596
% samples above detection	98	98	94	97	95	86	76	99
All Freeway Areas Combined (680)								
COV	2.6	1.0	2.7	1.2	5.2	2.2	1.1	1.4
Median	53.0	64.0	2000	1.7	0.3	17.8	49.0	100.0
Number of samples	360	439	67	430	585	340	355	587
% samples above detection	100	100	100	99	99	99	99	99
All Institutional Areas Combined (24)								
COV	1.1	1.0	0.4	0.6	0.9	0.6	1.0	0.9
Median	18.0	37.5	3400	1.1	0.2	21.5	8.6	198.0
Number of samples	23	22	3	22	23	21	21	22
% samples above detection	96	91	100	91	96	57	86	100
All Open-Space Areas Combined (79)								
COV	1.8	0.6	1.2	1.2	1.5	0.4	0.9	0.8
Median	10.5	21.3	2300	0.4	0.0	9.0	48.0	57.0
Number of samples	72	12	7	50	77	15	10	16
% samples above detection	97	83	100	96	97	47	20	50

NOTE: The complete database is located at: http://unix.eng.ua.edu/~rpitt/Research/ms4/mainms4.shtml. SOURCE: National Stormwater Quality Database.

In terms of regional differences, significantly higher concentrations of TSS, BOD_5, COD, total phosphorus, total copper, and total zinc were observed in arid and semi-arid regions compared to more humid regions. In contrast, fecal coliforms and total dissolved solids were found to be higher in the upper Midwest. More detailed discussions of land use and regional differences in stormwater quality can be found in Maestre et al. (2004) and Maestre and Pitt (2005, 2006). In addition to the information presented above, numerous researchers have conducted source area monitoring to characterize sheet flows originating from urban surfaces (such as roofs, parking lots, streets, landscaped areas, storage areas, and loading docks). The reader is referred to Pitt et al. (2005a,b,c) for much of this information.

Industrial Stormwater Characteristics

The NSQD, described earlier, has shown that industrial-area stormwater has higher concentrations of most pollutants compared to other land uses, although the variability is high. MS4 monitoring activities are usually conducted at outfalls of drainage systems containing many individual industrial activities, so discharge characteristics for specific industrial types are rarely available. This discussion provides some additional information concerning industrial stormwater beyond that included in the previous discussion of municipal stormwater. In general, there is a profound lack of data on industrial stormwater compared to municipal stormwater, and a correspondingly greater uncertainty about industrial stormwater characteristics.

The first comprehensive monitoring of an industrial area that included stormwater, dry weather base flows, and snowmelt runoff was conducted in selected Humber River catchments in Ontario (Pitt and McLean, 1986). Table 3-5 shows the annual mass discharges from the monitored industrial area in North York, along with ratios of these annual discharges compared to discharges from a mixed commercial and residential area in Etobicoke. The mass discharges of heavy metals, total phosphorus, and COD from industrial stormwater are three to six times that of the mixed residential and commercial areas.

TABLE 3-5 Annual Storm Drainage Mass Discharges from Toronto-Area Industrial Land Use

Measured parameter	units	annual mass discharges from industrial drainage area	stormwater annual discharge ratio (industrial compared to residential and commercial mixed area)
Runoff volume	m^3/hr/yr	6,580	1.6
total solids	kg/ha/yr	6,190	2.8
total phosphorus	kg/ha/yr	4,320	4.5
TKN	g/ha/yr	16,500	1.2
COD	kg/ha/yr	662	3.3
Cu	g/ha/yr	416	4.0
Pb	g/ha/yr	595	4.2
Zn	g/ha/yr	1,700	5.8

SOURCE: Pitt and McLean (1986).

Hotspots of contamination on industrial sites are a specific concern. Stormwater runoff from "hotspots" may contain loadings of hydrocarbons, trace metals, nutrients, pathogens and/or other toxicants that are greater than the loadings of "normal" runoff. Examples of these hotspots include airport de-icing facilities, auto recyclers/junkyards, commercial garden nurseries, parking lots, vehicle fueling and maintenance stations, bus or truck (fleet) storage areas, industrial rooftops, marinas, outdoor transfer facilities, public works storage areas, and vehicle and equipment washing/steam cleaning facilities (Bannerman et al., 1993; Pitt et al., 1995; Claytor and Schueler, 1996).

The elevated concentrations and mass discharges found in stormwater at industrial sites are associated with both the activities that occur and the materials used in industrial areas, as discussed in the sections that follow.

Effects of Roofing Materials on Stormwater Quality

The extensive rooftops of industrial areas can be a significant pollutant source area. A summary of the literature on roof-top runoff quality, including both roof surfaces and underlying materials used as subbases (such as treated wood), is presented in Table 3-6. Good (1993) found that dissolved metals' concentrations and toxicity remained high in roof runoff samples, especially from rusty galvanized metal roofs during both first flush and several hours after a rain has started, indicating that metal leaching continued throughout the events and for many years. During pilot-scale tests of roof panels exposed to rains over a two-year period, Clark et al. (2008) found that copper roof runoff concentrations for newly treated wood panels exceeded 5 mg/L (a very high value compared to median NSQD stormwater concentrations of about 10 to 40 µg/L for different land uses) for the first nine months of exposure. These results indicated that copper continued to be released from these wood products at levels high enough to exceed aquatic life criteria for long periods after installation, and were not simply due to excess surface coating washing off in the first few storms after installation.

Traditional unpainted or uncoated hot-dip galvanized steel roof surfaces can also produce very high zinc concentrations. For example, pilot-scale tests by Clark et al. (2008) indicated that zinc roof runoff concentrations were 5 to 30 mg/L throughout the first two years of monitoring of a traditional galvanized metal panel. These are very high values compared to median stormwater values reported in the NSQD of 60 to 300 µg/L for different land uses. Factory-painted aluminum–zinc alloy panels had runoff zinc levels less than 250 µg/L, which were closer to the reported NSQD median values. The authors concluded that traditional galvanized metal roofing contributed the greatest concentrations of many metals and nutrients. In addition, they found that pressure-treated and waterproofed wood contributed substantial copper loads. The potential for nutrient release exists in many of the materials tested (possibly as a result of phosphate washes and binders used in the material's preparation or due to natural degradation).

Other researchers have investigated the effects of industrial rooftop runoff on receiving waters and biota. Bailey et al. (1999) investigated the toxicity to juvenile rainbow trout of runoff from British Columbia sawmills and found that much of the toxicity may have been a result of divalent cations on the industrial site, especially zinc from galvanized roofs.

TABLE 3-6 Roof Runoff Analysis—A Literature Summary

Roof Type	Location	Water Quality Parameter								Reference
		Cu (μg/L)	Zn (μg/L)	Pb (μg/L)	Cd (μg/L)	As (μg/L)	pH	NH_4^+ (mg/L)	NO_3^- (mg/L)	
Polyester	Duebendorf, Switzerland	6817	2076	510	3.1					Boller (1997)
Tile		1905	360	172	2.1					
Flat gravel		140	36	22	0.2					
Plywood w/ roof paper/tar	Washington	$166^{T}/128^{D}$	$877^{T}/909^{D}$	$11^{T}/<5^{D}$			4.3			Good (1993)
Rusty galvanized metal		$20^{T}/2^{D}$	$12200^{T}/11900^{D}$	$302^{T}/35^{D}$			5.9			
Old metal w/Al paint		$11^{T}/7^{D}$	$1980^{T}/1610^{D}$	$10^{T}/<5^{D}$			4.8			
Flat tar surface w/fibrous reflective Al paint		$25^{T}/14^{D}$	$297^{T}/257^{D}$	$10^{T}/5^{D}$			4.1			
New anodized Al		$16^{T}/7^{D}$	$101^{T}/82^{D}$	$15^{T}/<5^{D}$			5.9			
Zinc-galvanized Fe	Dunedin City, New Zealand	560 μg/g	5901 μg/g	670 μg/g						Brown & Peake (2006)
Fe-Zn sheets	Ile-Ife, Nigeria						6.77	0.06	1.52	Adeniyi and Olabanji (2005)
Concrete slate tiles							7.45	0.05	3.34	
Asbestos cement sheets							7.09	0.06	2.26	
Aluminum sheets							6.68	0.05	6.18	
Cu panels	Munich, Germany	200–11100					6.7–7.0			Athanasiadis et al. (2006)
Galvanized metals (primarily Galvalume®)	Seattle, WA	10–1400	420–14700	ND						Tobiason (2004)
CCA wood	Florida					1200–1800				Khan et al. (2006)
Untreated wood						2–3				

Note: D, dissolved; T, total; ND, not detected.

SOURCE: Reprinted, with permission, from Clark et al. (2008). Copyright 2008 by American Society of Civil Engineers.

Effects of Pavement and Pavement Maintenance on Stormwater Quality

Pavement surfaces can also have a strong influence on stormwater runoff quality. For example, concrete is often mixed with industrial waste sludges as a way of disposing of the wastes. However, this can lead to stormwater discharges high in toxic compounds, either due to the additives themselves or due to the mobilization of compounds via the additives. Salaita and Tate (1998) showed that high levels of aluminum, iron, calcium, magnesium, silicon, and sodium were seen in the cement-waste samples. A variety of sands, including waste sands, have been suggested as potential additives to cement and for use as fill in roadway construction. Wiebusch et al. (1998) tested brick sands and found that the higher the concentration of alkaline and alkaline earth metals in the samples, the more easily the heavy metals were released. Pitt et al. (1995) also found that concrete yard runoff had the highest toxicity (using Microtox screening methods) observed from many source areas, likely due to the elevated pH (about 11) from the lime dust washing off from the site.

The components of asphalt have been investigated by Rogge et al. (1997), who found that the majority of the elutable organic mass that could be identified consisted of *n*-alkanes (73 percent), carboxylic acids such as *n*-alkanoic acids (17 percent), and benzoic acids. PAHs and thiaarenes were 7.9 percent of the identifiable mass. In addition, heterocyclic aromatic hydrocarbons containing sulfur (S-PAH), such as dibenzothiophene, were identified at concentration levels similar to that of phenanthrene. S-PAHs are potentially mutagenic (similar to other PAHs), but due to their slightly increased polarity, they are more soluble in water and more prone to aquatic bioaccumulation.

In addition to the bitumens and asphalts, other compounds are added to paving (and asphaltic roofing) materials. Chemical modifiers are used both to increase the temperature range at which asphalts can be used and to prevent stripping of the asphalt from the binder. A variety of fillers may also be used in asphalt pavement mixtures. The long-term environmental effects of these chemicals in asphalts are unknown. Reclaimed asphalt pavements have also been proposed for use as fill materials for roadways. Brantley and Townsend (1999) performed a series of leaching tests and analyzed the leachate for a variety of organics and heavy metals. Only lead from asphalt pavements reclaimed from older roadways was found to be elevated in the leachate.

Stormwater quality from asphalt-paved surfaces seems to vary with time. Fish kills have been reported when rains occur shortly after asphalt has been installed in parking areas near ponds or streams (Anonymous, 2000; Perez-Rivas, 2000; Kline, 2002). It is expected that these effects are associated with losses of the more volatile and toxic hydrocarbons that are present on new surfaces. It is likely that the concentrations of these materials in runoff decrease as the pavement ages. Toxicity tests conducted on pavements several years old have not indicated any significant detrimental effects, except for those associated with activities conducted on the surface (such as maintenance and storage of heavy equipment; Pitt et al., 1995, 1999). However, pavement maintenance used to "renew" the asphalt surfaces has been shown to cause significant problems, which are summarized below.

A significant source of PAHs in the Austin, Texas, area (and likely elsewhere) has been identified as coal-tar sealants commonly used to "restore" asphalt parking lots and storage areas. Mahler et al. (2005) found that small particles of sealcoat that flake off due to abrasion by vehicle tires have PAH concentrations about 65 times higher than for particles washed off parking lots that are not seal coated. Unsealed parking lots receive PAHs from the same urban sources as do sealed parking lots (e.g., tire particles, leaking motor oil, vehicle exhaust, and atmospheric fallout), and yet the average yield of PAHs from the sealed parking lots was found to be 50 times greater than that from the control lots. The authors concluded that sealed parking lots could be the dominant source of PAHs in watersheds that have seal-coated surfaces, such as many industrial, commercial, and residential areas. Consequently, the City of Austin has restricted the use of parking lot coal-tar sealants, as have several Wisconsin communities.

Stored Materials Exposed to Rain

Although roofing and pavement materials make up a large fraction of the total surface covers and can have significant effects on stormwater quality, leaching of rain through stored materials may also be a significant pollutant source at industrial sites. Exposed metals in scrap yards can result in very high concentrations of heavy metals. For example, Table 3-7 summarizes data from three metals recycling facilities/scrap yards in Wisconsin and shows the large fraction of metals that are either dissolved in the runoff or associated with very fine particulate matter. For most of these metals, their greatest abundance is associated with the small particles (<20 μm in diameter), and relatively little is associated with the filterable fraction. These metals concentrations (especially zinc, copper, and lead) are also very high compared to that of most outfall industrial stormwater.

TABLE 3-7 Metal Concentration Ranges Observed in Scrapyard Runoff

Particle Size	**Iron (mg/L)**	**Aluminum (mg/L)**	**Zinc (mg/L)**
Total	20 – 810	15 – 70	1.6 – 8
< 63 μm diameter	22 – 767	15 – 58	1.5 – 7.6
< 38 μm diameter	21 – 705	15 – 58	1.4 – 7.4
< 20 μm diameter	15 – 534	12 – 50	1.1 – 7.2
< 0.45 μm diameter (filterable fraction)	0.1 – 38	0.1 – 5	0.1 – 6.7
	Copper (mg/L)	**Lead (mg/L)**	**Chromium (mg/L)**
Total	1.1 – 3.8	0.6 – 1.7	0.1 – 1.9
< 63 μm diameter	1.1 – 3.6	0.1 – 1.6	0.1 – 1.6
< 38 μm diameter	1.1 – 3.3	0.1 – 1.6	0.1 – 1.4
< 20 μm diameter	1.0 – 2.8	0.1 – 1.6	0.1 – 1.2
< 0.45 μm diameter (filterable fraction)	0.1 – 0.3	0.1 – 0.3	0.1 – 0.3

SOURCE: Reprinted, with permission, from Clark et al. (2000). Copyright 2000 by Shirley Clark.

OTHER SOURCES OF URBAN RUNOFF DISCHARGES

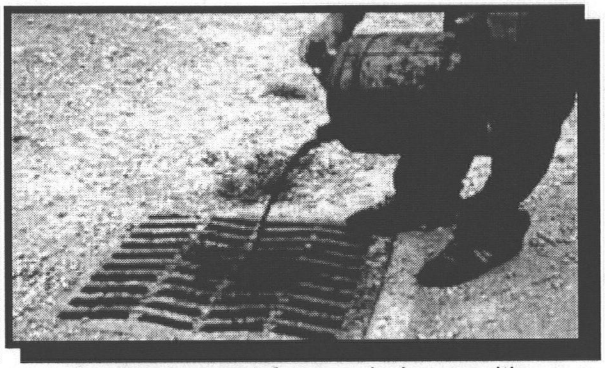
Wet weather stormwater discharges from separate storm sewer outfalls are not the only discharges entering receiving waters from these systems. Dry weather flows, snowmelt, and atmospheric deposition all contribute to the pollutant loading of urban areas to receiving waters, and for some compounds may be the largest contributor. Many structural SCMs, especially those that rely on sedimentation or filtration, have been designed to function primarily with stormwater and are not nearly as effective for dry weather discharges, snowmelt, or atmospheric deposition because these nontraditional sources vary considerably in key characteristics, such as the flow rate and volume to be treated, sediment concentrsations and particle size distribution, major competing ions, association of pollutants with particulates of different sizes, and temperature. Information on the treatability of stormwater vs. snowmelt and other nontraditional sources of urban runoff can be found in Pitt and McLean (1986), Pitt et al. (1995), Johnson et al. (2003), and Morquecho (2005).

Dry Weather Flows

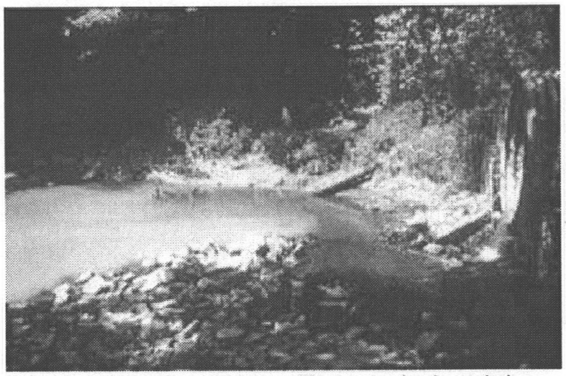
At many stormwater outfalls, discharges occur during dry weather. These may be associated with discharges from leaking sanitary sewer and drinking water distribution systems, industrial wastewaters, irrigation return flows, or natural spring water entering the system. Possibly 25 percent of all separate stormwater outfalls have water flowing in them during dry weather, and as much as 10 percent are grossly contaminated with raw sewage, industrial wastewaters, and so forth (Pitt et al., 1993). These flow contributions can be significant on an annual mass basis, even though the flow rates are relatively small, because they have long duration. This is particularly true in arid areas, where dry weather discharges can occur daily. For example, despite the fact that rain is scarce from May to September in Southern California, an estimated 40 to 90 million liters of discharge flow per day into Santa Monica Bay through approximately 70 stormwater outlets that empty onto or across beaches (LAC DPW, 1985; SMBRP, 1994), such that the contribution of dry weather flow to the total volume of runoff into the bay is about 30 percent (NRC, 1984). Furthermore, in the nearby Ballona Creek watershed, dry weather discharges of trace metals were found to comprise from 8 to 42 percent of the total annual loading (McPherson et al., 2002). Stein and Tiefenthaler (2003) further found that the highest loadings of metals and bacteria in this watershed discharging during dry weather can be attributed to a few specific stormwater drains.

In many cases, stormwater managers tend to overlook the contribution of dry weather discharges, although the EPA's NPDES Stormwater Permit program requires municipalities to conduct stormwater outfall surveys to identify, and then correct, inappropriate discharges into separate storm sewer systems. The role of inappropriate discharges in the NPDES Stormwater Permit program, the developed and tested program to identify and quantify their discharges, and an extensive review of these programs throughout the United States can be found in the recently updated report prepared for the EPA (CWP and Pitt, 2004). The following photographs show various nontraditional sources of contaminants in urban runoff.

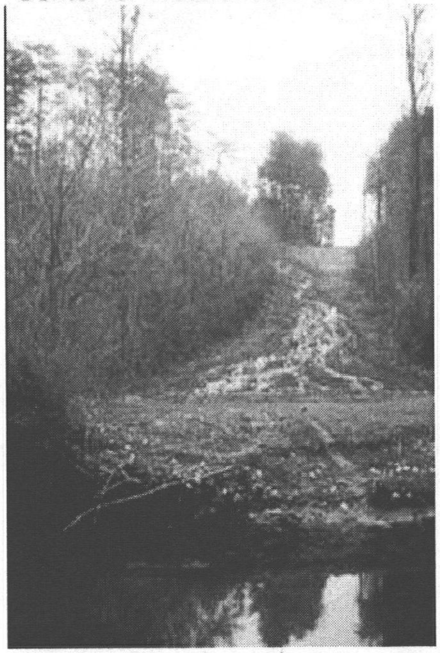
Washing of vehicle engine and allowing runoff to enter storm drainage system. SOURCE: Robert Pitt.



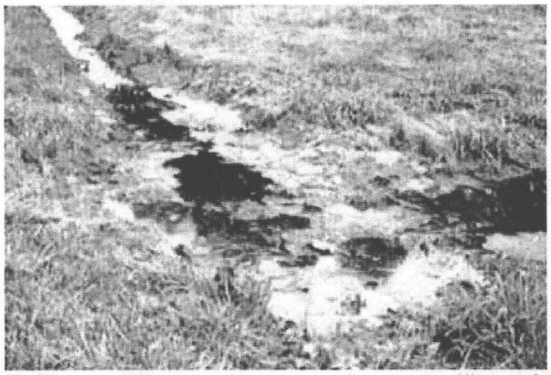
Contamination of storm drainage with inappropriate disposal of oil. SOURCE: Center for Watershed Protection.



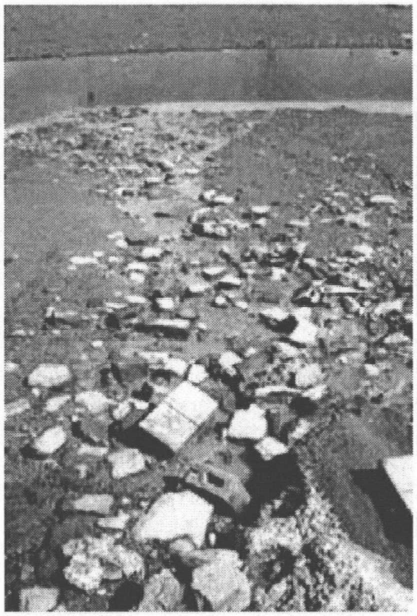
Dry weather flows from Toronto industrial area outfall. SOURCE: Pitt and McLean (1986).



Sewage from clogged system overflowing into storm drainage system. SOURCE: Robert Pitt.



Failing sanitary sewer, causing upwelling of sewage through soil, and draining to gutter and then to storm drainage system.
SOURCE: Robert Pitt.



Dye tests to confirm improper sanitary sewage connection to storm drainage system SOURCE: Robert Pitt.

Snowmelt

In northern areas, snowmelt runoff can be a significant contributor to the annual discharges from urban areas through the storm drainage system. In locations having long and harsh winters, with little snowmelt until the spring, pollutants can accumulate and be trapped in the snowpack all winter until the major thaw when the contaminants are transported in short-duration events to the outfalls (Jokela, 1990). The sources of the contaminants accumulating in snowpack depend on the location, but they usually include emissions from nearby motor vehicles and heating equipment and industrial activity in the neighborhood. Dry deposition of sulfur dioxide from industrial and power plant smokestacks affects snow packs over a wider area and has frequently been studied because of its role in the acid deposition process (Cadle, 1991). Pollutants are also directly deposited on the snowpack. The sources of directly deposited pollutants include debris from deteriorated roadways, vehicles depositing petroleum products and metals, and roadway maintenance crews applying salt and anti-skid grit (Oberts, 1994). Urban snowmelt, like rain runoff, washes some material off streets, roofs, parking and industrial storage lots, and drainage gutters. However, snowmelt runoff usually has much less energy than striking rain and heavy flowing stormwater. Novotny et al. (1986) found that urban soil erosion is reduced or eliminated during winter snow-cover conditions. However, erosion of bare ground at construction sites in the spring due to snowmelt can still be very high.


Snowmelt. SOURCE: Roger Bannerman.

Construction site in early spring after snowmelt showing extensive sediment transport. SOURCE: Roger Bannerman.

Sources of Contaminants in Snowmelt

Several mechanisms can bring about contamination of snow and snowmelt waters. Initially, air pollutants can be incorporated into snowflakes as they form and fall to the ground. After it falls to the ground and accumulates, the snow can become further contaminated by dry atmospheric deposition, deposition of nearby lost fugitive dust materials (usually blown onto snow packs near roads by passing vehicles), and wash off of particulates from the exposed ground surfaces as it melts and flows to the drainage system.

Snowflakes can remove particulates and gases from the air by in-cloud or below-cloud capture. In-cloud capture of pollutants can occur during snowflake formation as super-cooled cloud water condenses on particles and aerosols that act as cloud condensation nuclei. This is known as nucleation scavenging and is a major pathway for air pollution to be incorporated into snow. Particles and gases may also be scavenged as snowflakes fall to the ground. Gases can also be absorbed as snow falls. Snowflakes are more effective below-cloud scavengers than raindrops because they are bigger and fall slower. Barrie (1991) reports that large snowflakes