CDM

Assabet River Sediment and Dam Removal Study

Modeling Report

Prepared for:

U.S. Army Corps of Engineers
New England District

June 2008

Executive Summary

Phosphorus concentrations in the Assabet River, located approximately 20 miles west of Boston, MA, are causing excessive production of floating and rooted aquatic macrophytes. Phosphorus loadings originate from both non-point sources and point sources such as Wastewater Treatment Facilities (WWTFs). The U.S. Environmental Protection Agency (EPA) and the Massachusetts Department of Environmental Protection (MADEP) approved a Total Maximum Daily Load (TMDL) that requires reductions of phosphorous loadings from the WWTFs that discharge to the river and a 90 percent reduction in sediment phosphorous load in order to achieve water quality compliance.

The purpose of the Assabet River Sediment and Dam Removal study is to achieve water quality compliance and a sustainable and restored aquatic ecosystem. The study involves identifying and assessing alternatives for reducing internal phosphorus recycling from sediments through sediment removal, sediment treatment, or dam removal. Six dams were evaluated for sediment and/or dam removal in this study.

USACE contracted with CDM to perform data collection and modeling tasks in order to assess alternatives such as sediment removal and dam removal. The modeling efforts included evaluating changes in water surface, downstream movement of sediment behind the dam, and changes in water quality due to changes in sediment phosphorus release rates and hydraulic changes for various sediment and dam removal alternatives.

Results of this study suggest that the most beneficial water quality improvements to the Assabet River can be achieved through planned WWTF improvements, dam removal, and consideration of lower winter effluent limits than currently planned. Study findings are summarized as follows.

- Expect reduction of 60% of sediment phosphorus flux from planned WWTF improvements (Phosphorus discharge limit of 0.1 mg/l summer and 1.0 mg/l winter).
- Remove Ben Smith dam and if possible, Gleasondale and Hudson/Rt 85 dams. Remove sediment behind dams as part of dam removal to prevent sediment from moving downstream subsequent to dam removal.
- Lower winter WWTP Phosphorus discharge below 1.0 mg/l
- Results suggest that dredging or sediment removal is not effective in reducing sediment flux. Dredging/sediment removal is proposed in conjunction with dam removal to prevent the redistribution of accumulated sediment.
- Nonpoint source reductions, including Phase II stormwater management and enhanced golf course management, should be considered.

- An adaptive strategy would have advantages, since the response of the river to above alternatives is anticipated to occur within a few years. The planned WWTF improvements should proceed, and impacts should be measured concurrently with the process of planning and design for dam removal. It may also be beneficial to test the impacts of lower winter effluent phosphorus limits in the near term, since this study suggests this winter limits significantly impact sediment phosphorus flux rates in the following growing seasons.

Of the alternatives evaluated in this study, no alternative or combination of alternatives is projected to result in a 90 percent reduction in phosphorus flux. It should be noted, however, that several of the alternatives would contribute to water quality and environmental restoration goals for the Assabet River.

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Introduction

1.1 Background

Phosphorus concentrations in the Assabet River, located approximately 20 miles west of Boston, MA, are causing excessive production of floating and rooted aquatic macrophytes. This results in Massachusetts Water Quality Standards violations for dissolved oxygen, eutrophication and aesthetics. Phosphorus loadings originate from both point sources and non-point sources. Point sources include four publicly owned wastewater treatment facilities (WWTFs), the Powdermill Plaza WWTF in Acton, and a small institutional wastewater treatment facility at MCI Concord. Non-point sources include internal recycling of phosphorus from sediments and stormwater runoff.

The U.S. Environmental Protection Agency (EPA) and the Massachusetts Department of Environmental Protection (MADEP) approved a Total Maximum Daily Load (TMDL) that requires reductions of phosphorous loadings from the four municipal WWTFs that discharge to the river and a 90 percent reduction in sediment phosphorous load in order to achieve water quality compliance. Once phosphorus loads are reduced from the WWTFs, internal recycling from sediments will continue to supply biologically available phosphorus to the river.

The NPDES permits for the four publicly owned WWTFs require facility upgrades to achieve 0.1 mg/l of effluent phosphorus during the summer months (April through October) and 1.0 mg/l in the winter months (November through March) by 2010. The current NPDES permit limits allow for phosphorus levels to 0.75 mg/l in effluent during the summer months and no limit during the winter months (although most WWTFs discharge between 1 and 2 mg/l in the winter months). The current limits apply until plant upgrades are completed in 2010 or 2011.

1.2 Study Purpose

The purpose of the Assabet River Sediment and Dam Removal study is to achieve water quality compliance and a sustainable and restored aquatic ecosystem. The study involves identifying and assessing alternatives for reducing internal phosphorus recycling from sediments through sediment removal, sediment treatment, or dam removal. Major goals of the study include:

- **Water Quality**. The restored system must meet Massachusetts State Water Quality Standards for dissolved oxygen, acceptable levels of biomass production, and acceptable ambient phosphorus concentrations.

- **Ecosystem restoration**. Improve and restore a combination of habitats in different portions of the river that support both typical warm-water species and fluvial dependents and anadromous species such as American eel and alewife.

1.3 Study Authority

The study is being conducted by the New England District of the Corps of Engineers (USACE) under the Planning Assistance to States (PAS) Program (Section 22). The Massachusetts Department of Environmental Protection (MADEP) is participating in a cost sharing agreement with USACE.

1.4 Study Area Description

The Assabet River is located approximately 20 miles west of Boston. The river is 31 miles long and flows through the towns of Westborough, Northborough, Marlborough, Berlin, Hudson, Stow, Maynard, Acton and Concord where it joins the Sudbury River to form the Concord River. The drainage area to the river is 177 square miles.

Average monthly flows in the River (USGS gage at Maynard) range from about 400 cubic feet per second (cfs) in March to about 60 cfs in August.

Seven dams are on the mainstem of the Assabet River. Six of these dams are included in this study, and were investigated as potential options for dam removal, including the Aluminum City dam and Allen Street dam in Northborough, the Hudson/Rt 85 dam in Hudson, the Gleasondale dam in Stow, the Ben Smith dam in Maynard, and the Powdermill dam in Acton. The Tyler dam is a flood control dam and is also located on the mainstem of the Assabet River, but is not being evaluated for removal.

A profile of the Assabet River, including locations of the dams and WWTFs is included in Figure 1-1.

1.5 Study Team

In addition to the USACE New England District and MADEP leading the study, MA DEP entered into a Memorandum of Understanding with the six Assabet River Consortium communities (Marlboro, Shrewsbury, Westboro, Northboro, Hudson, and Maynard) regarding the study. The MOU established a Study Coordination Team (SCT) made up of twelve members, six from the communities and six selected by MADEP including Organization for the Assabet River (OAR).

1.6 Modeling Study

USACE contracted with CDM to perform data collection and modeling tasks, including field data collection, model development, model runs and analysis described in this report. Collected data, modeling and analysis was used to assess alternatives such as sediment removal and dam removal. Specific modeling tasks included:

- Simulating Effects of Dam Removal
    - Changes in water surface during normal and flood flow conditions
    - Downstream movement of sediment behind the dam
    - Changes in water quality due to changes in sediment phosphorus release rates and hydraulic changes (water depth and velocity).
- Simulating Effects of Sediment Removal
    - Changes in water quality due to changes in sediment phosphorus release rates and hydraulic changes (water depth and velocity).

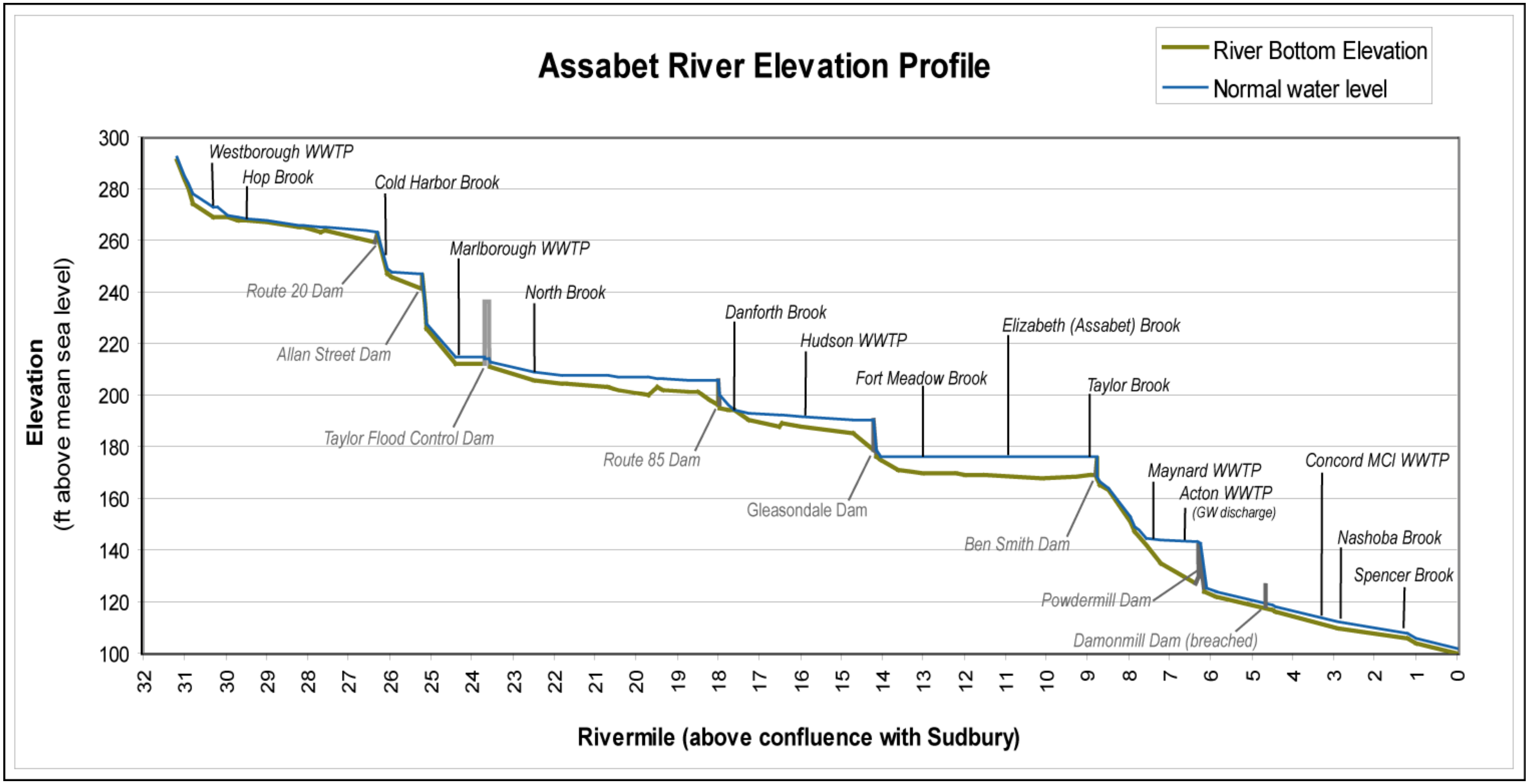


Figure 1-1 Assabet River Elevation Profile
Source: OAR (For Conceptual Reference Only)

Section 2
Modeling Methodology

This section presents the modeling approach used to evaluate alternative strategies to improve the overall conditions in the Assabet River. Computer simulation models were used to evaluate the impacts of dam removal and dredging on the following:

- Water surface profiles during high and low flow conditions
- Sediment volumes and mobility
- Water quality, specifically its dependence on hydraulics and sediment nutrient flux

The modeling approach required the collection of some additional data, which is discussed in Section 3 and Appendix A of this report.

2.1 Modeling Objectives

An HSPF model was developed by ENSR International to examine the water quality of the Assabet River. Sources of pollution include non-point sources such as stormwater runoff, and point sources such as wastewater treatment plants. The HSPF model simulates instream chemical and biological processes associated with dissolved oxygen, nitrogen, phosphorus, BOD, phytoplankton (Chlorophyll *a*) and plant biomass. The findings from the HSPF model were used in establishing the TMDL for the river.

As part of the current study, detailed questions on the effects of dam removal and sediment removal were posed (See Table 2-1). Refinement of the HSPF model and supplemental models were needed to effectively answer questions relating to the analysis of existing conditions, system sensitivity, and potential alternatives for sediment and/or dam removal. Specifically, the hydraulics and sediment flux representation in the HSPF model required significant reformulation, and separate models for river hydralics, sediment transport, and sediment flux were developed, both to answer individual questions on their own, and to support refinements in the HSPF model.

Table 2-1. Questions to be Addressed or Confirmed with Modeling

Analysis	Modeling Questions
Existing Conditions	Confirm the residence time in the impoundments under high flow and low flow conditions
	Confirm the travel time in the river under different hydrologic conditions
	What are existing sediment flux rates (phosphorus) under aerobic and anaerobic conditions, both in impoundments and in riverine sections?
	What are existing contributions of phosphorus from WWTPs, sediments, and NPS?
Alternatives Analysis	How would river hydraulics change if dams were removed?
	How would sediments be redistributed if dams were removed?
	How would water quality change if dams were removed?
	How would water quality change if sediments were dredged?
Additional Analysis*	How responsive is sediment flux to seasonal variations in overlying water column concentration?

**This question arose during the course of the study, as field data suggested that a more complete understanding of annual dynamics of nutrients in the sediments was key to understanding the potential for improved water quality in the river.*

2.2 Previous Modeling

As discussed earlier, the HSPF model was applied to the Assabet River watershed by ENSR, and this model and its results are described in their 2005 report to MADEP entitled *SuAsCo Watershed, Assabet River TMDL Study, Phase 2: Analysis.*. The application used, HSPF v 10, is a complex, time variable (dynamic) approach that simulates hydrology generated from precipitation and specified land uses in the watershed. It predicts in-stream water quality for several variables. HSPF was used to develop, calibrate, and verify a model for the Assabet River based on conditions monitored in 1999 and 2000. Results were used to establish Total Maximum Daily Loads (TMDLs) for point sources in the watershed.

2.3 Model Roles and Functionality

No single model was deemed sufficient to address the questions in Table 2-1 with enough resolution to provide substantive and comprehensive guidance. The existing HSPF model was used in a limited capacity, and additional models were developed to address specific questions, or to provide more detailed information on hydraulics and sediment characteristics to improve the parameterization of the HSPF model. The functions of the models used in this study are identified in Table 2-2, and each model is discussed in the following paragraphs. Detailed information on how the models were developed and tested can be found in Section 4.

Table 2-2. Primary Model Functions

Model	Channel Profile	Channel Hydraulics	Watershed Flows & Loads	Instream Water Quality	Water Level	Sediment Flux Rates
HEC-6	✓					
HEC-RAS		✓			✓	
HSPF			✓	✓		
Phosphorus Flux						✓

2.3.1 HEC-RAS Model (Hydraulics)

The Army Corps' HEC-RAS model (Hydrologic Engineering Center – River Analysis System) was selected to simulate the hydraulics (backwater profiles, flow velocities, and water depth throughout the entire river) in the Assabet River. HEC-RAS calculates water surface profiles for steady or gradually varied flow. It uses explicit hydraulic relationships to simulate subcritical, supercritical, and mixed flow regimes. HEC-RAS is used extensively by FEMA for preparing Flood Insurance Studies.

HEC-RAS was used in two ways. The model was used as a stand-alone model to address questions related to the impacts of alternatives on water surface profiles and hydraulic characteristics. The HEC-RAS model was also used to tune, or refine, the hydraulic transport relationships within HSPF. The existing HSPF relied upon rating curves (stage-discharge relationships) at the downstream end of each simulated river reach to estimate the passage of water from one reach to the next. These curves were refined in HSPF by testing a variety of flow levels in HEC-RAS and associating variable discharge rates with water levels in each reach (see Section 2.3.3 below).

2.3.2 HEC-6 Model (Sediment Transport)

HEC-6 is a one-dimensional sediment transport model which calculates water surface and sediment bed surface profiles by computing the interaction between sediment material in the streambed and the flowing water-sediment mixture. It is a dynamic model that simulates the short-term and long-term morphography of the channel bed, and can be used to evaluate stabilization timeframes and sediment transport patterns once a riverbed is modified. It was used in this study to simulate the movement of sediment following dam removal, and changes to the riverbed profile following dredging.

2.3.3 Existing HSPF Model (Hydrology and Water Quality)

In 2005 ENSR International completed development of a water quality modeling application conducted in support of development of a Total Maximum Daily Load (TMDL) allocation for the Assabet River system. Results of the model were presented in a document titled "SuAsCo Watershed Assabet River TMDL Study Phase Two: Analysis Final Report" (ENSR, 2005). The Hydrologic Simulation Program Fortran (HSPF) was selected to model the Assabet River system because of its dynamic streamflow, watershed nutrient loading, and instream water quality simulation capabilities and is an EPA supported water quality model.

For this study, the existing HSPF model was used to generally assess either positive or negative changes in water quality associated with the alternatives under investigation (dam removal and dredging), but was not used to generate detailed quantitative water quality predictions. This is because the dam removal and dredging alternatives affect river characteristics that the HSPF model was not designed to evaluate explicitly, but which have a pronounced impact on water quality:

- Changes in water depth and residence times associated with dam removal and/or dredging
- Changes in phosphorus sediment release rates with changes in river bed sediment and dynamic (and seasonally variable) instream phosphorus/algal processes.
- Changes in instream water quality resulting from dam removal and/or sediment removal/movement.

HSPF is not a hydraulic simulation model. Flow is routed downstream using artificial rating curves for each simulated reach instead of explicit hydraulic relationships. This is not sufficient for determining the changes in the water depth and velocity from potential sediment and dam removal. Though HSPF has the capability to simulate the settling and re-suspension of solids (sediments), its limited hydraulics makes the solids model insufficient to address objectives of the Corps study.

Likewise, the user sets all sediment release rates in HSPF. Hence, the HSPF model cannot be used to address the issues of changes in phosphorus release rates in response to sediment removal, changes in water column chemistry, or changes in hydraulic conditions. The user must set the release rates that reflect the new sediment condition. To provide information on release rates, sediment release rates were measured at various locations in the river and a simple sediment mass balance model was developed as discussed in the following section. This data was used to estimate appropriate phosphorus release rates for future sediment conditions.

2.3.4 Additional Water Quality Modeling (Phosphorus Flux)

A spreadsheet model, developed based on equations from the USEPA QUAL2K model, was used to understand the dynamics of phosphorus flux in the system. The spreadsheet model was not intended to replace the HSPF model for simulating instream water quality dynamics. Rather, the model was used to further examine observed fluctuations in magnitude and direction of phosphorus fluxes to and from the sediment at various times of year, and as a function of both sediment and water column concentrations over time.

The model was used to help determine whether or not dredging would have long term benefits, or if the phosphorus flux rates in the Assabet River are generally more responsive to recent (seasonal) loads from the water column. The model was used to help distinguish impacts of historically accumulated nutrients in the sediment (past 30 – 50 years) from those of recently deposited nutrients from upstream sources (past 1-2 years). The model also helped identify flux rates for the HSPF model that were more reflective of observed data and could be theoretically substantiated.

2.4 Summary

The overall modeling process is depicted in the schematic in Figure 2-1. The figure illustrates how HEC-RAS was used to augment the HSPF model by providing more detailed hydraulic information to HSPF in areas in which the existing HSPF model was unable to address cause-and-effect relationships. It also illustrates how the sediment mass balance model was used to refine estimates of the sediment phosphorus flux. The sediment mass balance model was used in conjunction with the HSPF model to determine quantitative estimates of changes in sediment phosphorus flux under various proposed scenarios. Other than estimated changes in sediment phosphorus flux, the HSPF model was not used to examine specific changes in water quality. The HSPF model was limited to determining qualitatively whether or not each alternative would be beneficial or harmful with regard to other water quality parameters.

Table 2-3 identifies how the various models were used to address the questions listed in Table 2-1.

Figure 2-1: Schematic of Modeling Process

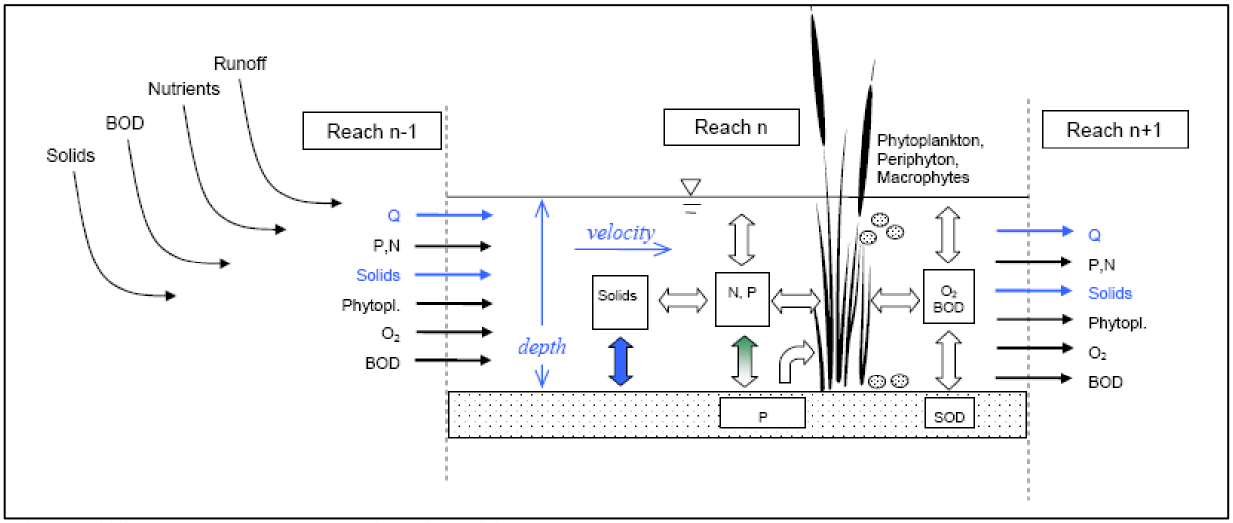


Figure illustrates processes simulated in HSPF.
Processes illustrated in blue were augmented by HEC-RAS.
Processes illustrated in green were refined with the sediment mass balance model.

Table 2-3: Use of Modeling Tools to Address Specific Questions

Type of Analysis	Foreseeable Modeling Questions	Primary	Supporting	
		HSPF	**HEC-RAS**	**P Flux**
Existing Conditions	Confirm the residence time in the impoundments under high flow and low flow conditions?		●	
	Confirm the travel time in the river under different hydrologic conditions?		●	
	What are existing sediment phosphorus flux rates under aerobic and anaerobic conditions, both in impoundments and in free-flowing stream?	●		○
	What are existing contributions of phosphorus from WWTPs, sediments, and NPS?	●		○
Alternatives Analysis	How would river hydraulics and wetland area change if dams were removed?		●	
	How would sediments be redistributed if dams were removed? *****		●	
	How would water quality change if dams were removed?	●	●	
	How would water quality change if sediments were dredged?	●		○
Additional Analysis*	How responsive is sediment flux to seasonal variations in overlying water column concentration?			●

● = Modeling required
○ = Based on modeling for other questions
* = Both HEC-RAS and HEC-6 models were used to evaluate sediment redistribution.

Section 3
Monitoring and Data Collection

Monitoring and modeling used to develop the TMDL provided a foundation from which to begin the current analysis. Additional data was required to support further modeling and analysis. A summary of both previous monitoring as well as data collected as part of the current modeling program is described in this section. For additional information on data collection efforts, the River Cross Section and Sediment Data Collection Field Investigation Technical Memorandum is included in Appendix A of this document.

3.1 Previous Monitoring

3.1.1 ENSR (1999-2000)

ENSR performed monitoring efforts, as part of the TMDL, in conjunction with MADEP and EPA. Monitoring conducted by ENSR is documented in a series of reports (see Section 7 – References). ENSR's monitoring program was completed in 1999-2000 and consisted of the following:

- Thirteen (13) field surveys - conducted from July 1999 through September 2000:
- Streamflow and time of travel measurements,
- Continuous measurements of dissolved oxygen concentration,
- Water column sampling and analysis of several nutrient constituent concentrations
- Nutrient load measurements from WWTFs,
- Non-point source nutrient loading measurements from tributaries,
- Sediment nutrient flux measurements, and
- Biological surveys

3.1.2 USGS Sediment Studies (2004-2005)

USGS, in cooperation with MADEP and EPA, performed sediment analysis in the six study impoundments. The work consisted of Part 1: Sediment Distribution and Chemistry in Six Impoundments in the Assabet River, and Part 2: Phosphorus Dynamics in a Wastewater-Dominated Impoundment, Hudson [USGS 2005]. This work included detailed measurements of bulk phosphorus concentrations in the impounded sediments, and also sediment flux rates (for phosphorus) in a representative impoundment (the Hudson impoundment).

3.2 Hydraulic Data Collection

3.2.1 Bridge and Structure Field Verification

As part of HEC-RAS model development, bridges and other structures were field verified and measured. Approximately 25 bridges and structures were field verified, measured and documented with photos and sketches for the purposes of inclusion in the HEC-RAS model. A summary of the bridge and structure verification, including the table of structures included in the field visits, is included in Appendix B of this document.

3.2.2 River Cross Sections

To develop the detailed HEC-RAS model, additional cross-sections of the river and accurate physical information on the dams and other critical structures were obtained. FEMA Flood Insurance Studies were obtained for each community and this information was used as the starting point in HEC-RAS model development.

Additional cross sections were also obtained through field efforts in areas where detailed study was not included in the Flood Insurance Studies. A total of 10 additional cross sections were surveyed by Normandeau Associates in December 2006. The purpose of the cross section surveys was to supplement and verify the HEC-RAS model. The surveyed cross sections included river channel geometry and bathymetry from four riverine sections in Northborough and locations just downstream from each of the six study dams.

Six of ten cross sections were surveyed immediate downstream of six dams; Aluminum City, Allen Street, Hudson, Gleasondale, Ben Smith, and Powdermill Dams. In addition, crest elevations of these six dams were also surveyed. These dam cross section and crest elevation data were used to verify dam structure data of the HEC-RAS model. Surveyed cross sections corresponded relatively well with the HEC-RAS cross sections. Dam crest elevations were adjusted according to surveyed data.

Two of ten cross sections were surveyed in the reach between Westborough and Northborough HEC-2 models, where no HEC-2 model existed. Two additional cross sections were surveyed in the reach between Northborough and Berlin HEC-2 models, where no HEC-2 model existed. These cross sections were added into the HEC-RAS model to supplement the gaps in the model.

Further detail on the cross sectional data is included in Appendix A.

3.3 Sediment and Water Quality Data Collection

3.3.1 Sediment Data Collection and Grain Size Analysis

Sediment grain size data was needed for the development of the sediment transport model. Grain size analysis was conducted collecting a total of eighteen sediment sample cores from the Assabet River, including 6 riverine samples and 12 impoundment samples:

- 6 riverine samples (S1-GA, S2-GA, S3-GA, S4-A, S5-A and S6-A)
- 12 impoundment samples - 2 samples collected from each impoundment – one from the downstream end and the other from the upstream portion of the impoundment (3A, 4A, 5A, 8A, 10A, 15A, 19A, 28A, 36A, 38A, 51A and 52A)

The riverine samples were collected by Normandeau Associates, Inc. in December 2006 while the impoundment samples were collected by USGS in 2003. The samples were analyzed for grain size using sieve (ASTM C136, C117) and hydrometer (ASTM D422-63) test methods. Figure 3-1 shows the sample locations relative to the river profile and the impoundments.

In general, the grain size distribution results indicated that the Assabet River sediment consists of a mix of sand and silt, with trace amounts of clay. Gravel was found at select locations with one riverine sample (S5) classified as gravel. Tables 3-1 and 3-2 provide a summary of the soil type classifications of the sediment.

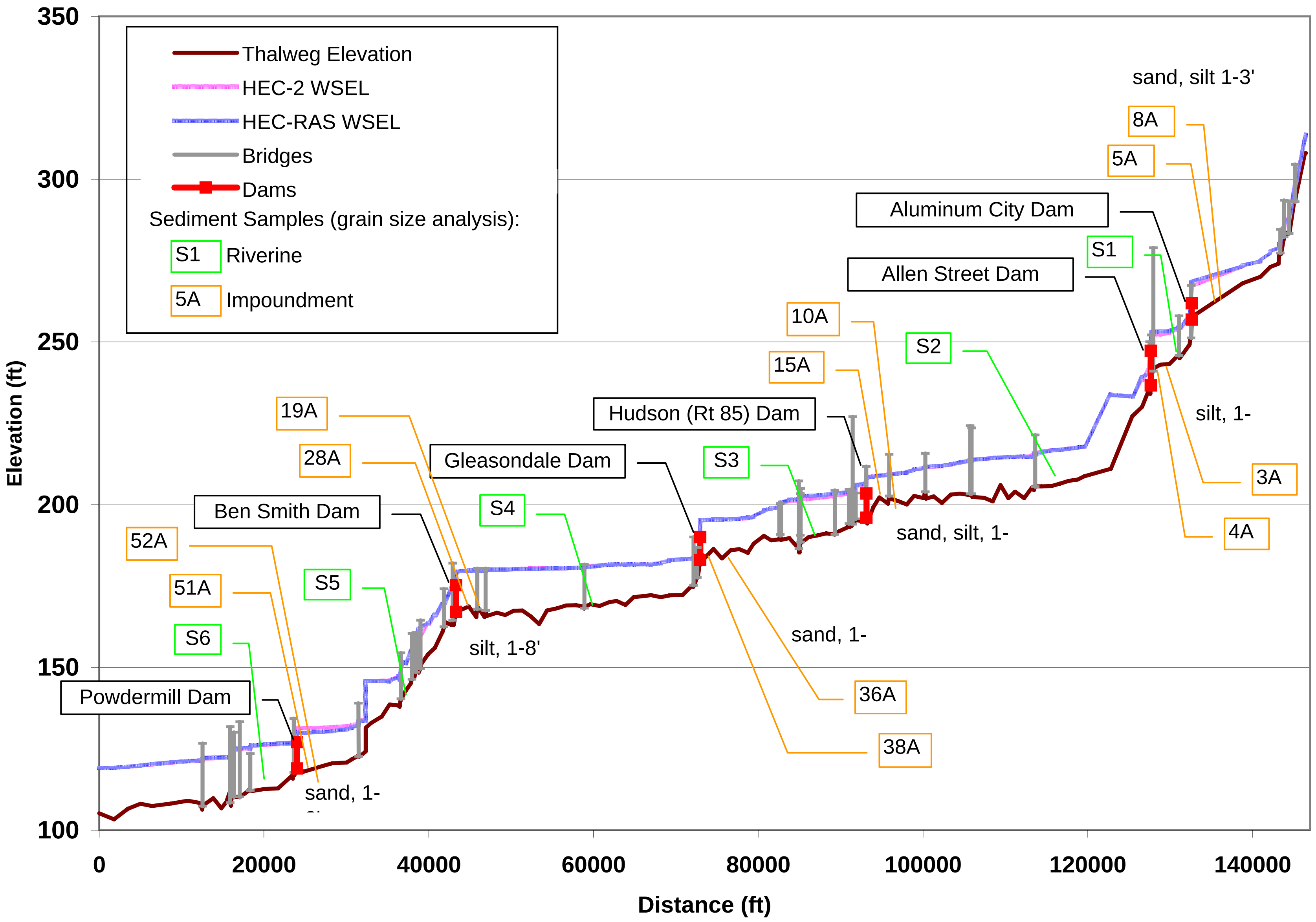


Figure 3-1 Sediment Sample Locations (November 2006)

Table 3-1. Soil Type Classification of Riverine Sediment Samples

Sample ID and Location		Soil Classification
S1	between Aluminum City and Allen St Dams	Dark brown medium to fine SAND, some silt, trace gravel
S2	between Allen St and Hudson Dams	Dark brown SILT, and medium to find sand
S3	between Hudson and Gleasondale Dams	Dark brown medium to fine SAND, little silt, trace clay
S4	between Gleasondale and Ben Smith Dams	Dark brown SILT, some medium to find sand, trace clay
S5	between Ben Smith and Powdermill Dams	Brown GRAVEL, and coarse to medium sand, trace silt
S6	downstream of Powdermill Dam	Dark brown medium to fine SAND, and silt, trace clay

Table 3-2. Soil Type Classification of Impoundment Sediment Samples

Impoundment	Soil Classification	
	Upper end	Downstream end
Aluminum City Dam (5A & 8A)	Dark brown fine SAND, and silt, trace clay and gravel	Dark brown SILT, and fine sand, trace clay
Allen St Dam (3A & 4A)	Dark brown SILT, and fine sand, trace clay	Dark brown SILT, some fine sand, trace clay
Hudson Dam (10A & 15A)	Dark brown medium to fine SAND, and silt, trace clay	Dark brown SILT, and fine sand, trace clay
Gleasondale Dam (36A & 38A)	Dark brown medium to fine SAND, little silt, trace clay	Dark brown fine SAND, and silt, trace clay
Ben Smith Dam (19A & 28A)	Dark brown SILT, little fine sane, trace clay	Brown SILT, some fine sand, trace clay
Powdermill Dam (52A & 51A)	Dark brown medium to fine SAND, some silt, trace clay	Dark brown fine SAND, and silt, trace clay

A brief summary of the grain size distribution analysis is as follows.

- In general, sediments contained greater amounts of fines in impoundments than in river reaches.
- Sediment materials consisted of sands and silts with trace amounts of clay; gravel was present in two samples.
- No correlation was observed between grain size distribution and river station.
- No correlation was observed between grain size distribution and water depth.

The average grain size distribution for both riverine and impoundment samples is shown in Figure 3-2. Additional details on the sediment data collection and the grain size distribution analysis is included in Appendix A.

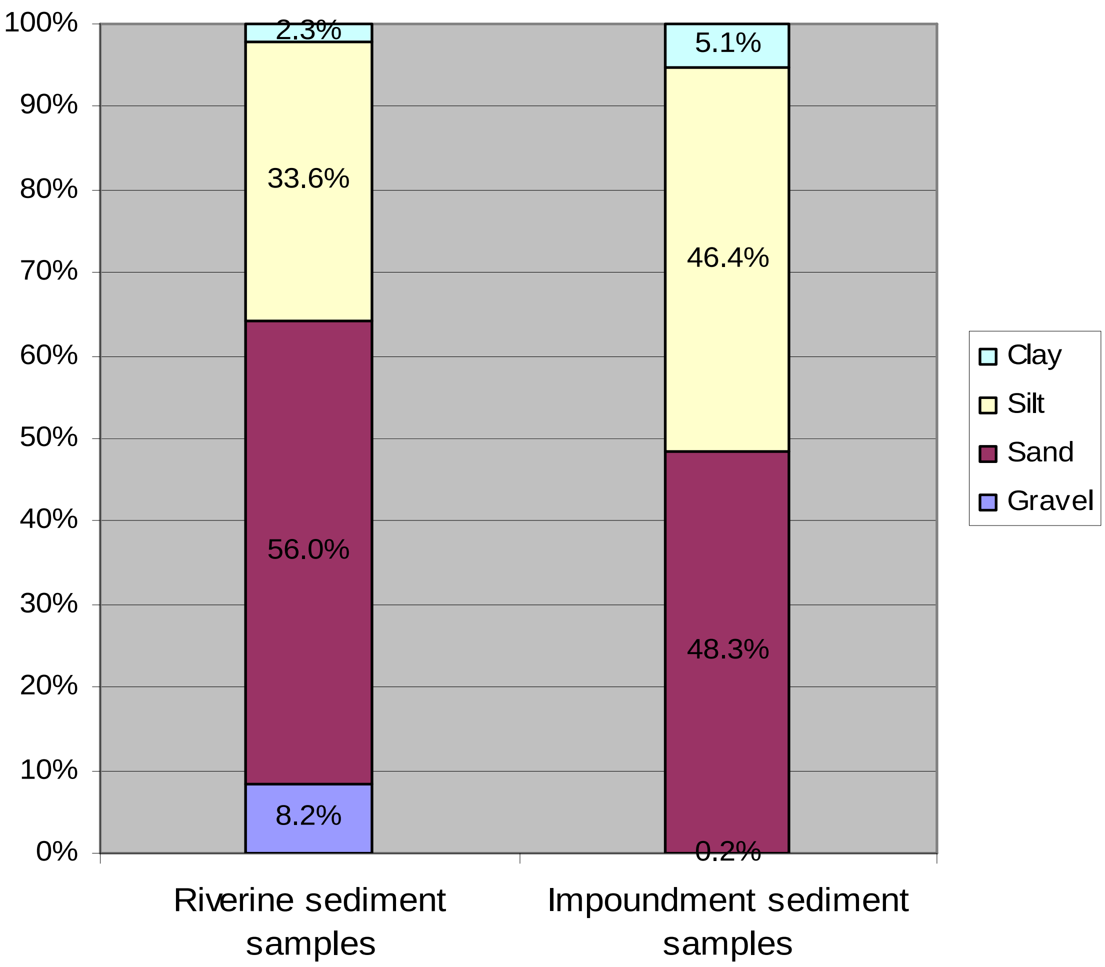


Figure 3-2. Average Grain Size Distribution, Assabet River Sediment Samples

3.3.1 Sediment Phosphorus Flux Measurements

Additional data was needed on the actual phosphorus flux rates in the river and impoundments. Sediment phosphorus flux rates were measured in all impoundments, as well as in several representative free-flowing reaches of the stream.

A total of 50 large diameter (7.25 cm) sediment cores were collected from November 30 – December 5 in the seven impoundments and in riverine sections. 42 of the samples taken were from the six study impoundments and A-1 at the headwater of the river, and eight sediment cores were taken from riverine stations. At each impoundment, 6 total cores were taken, including three samples at each location within the impoundment and 2 cores at each sample location (one aerobic, one anaerobic). The sample locations were spaced out through the impoundment area; one located at the downstream end of the impoundment near the dam, one located in the middle of the impoundment, and one located at the upstream end of the impoundment. Cores were also taken from 4 riverine locations (3 main stem locations and 1 tributary location). At each riverine location, 2 samples were taken (one aerobic, one anaerobic).

Cores were retrieved by hand coring, either by diver or rod-driven corer. Cores 50 cm long by 7.25 cm diameter, stoppered internally approximately 10 cm from the bottom, were hand forced into sediment to retrieve approximately 10 cm of undisturbed sediment. Cores were bottom capped underwater and stored upright for transport to the laboratory.

Approximately 25 gallons of river water were collected from flowing water upstream of the Aluminum City dam, for use in the laboratory.

The sediment phosphorus flux was then measured under controlled laboratory conditions, including both aerobic and anaerobic measurements, over a period of 25 days. Laboratory analyses followed ASTM guidelines, "Standard Test Method for Determining a Sorption Constant for an Organic Chemical in Soil and Sediments, (E-1195-01), ASTM 2002, with modifications based on USGS studies and lab protocols. Additional details on sample handling and laboratory methods are included in Envirosystems Inc. The Final Laboratory Report dated January 23, 2007, is included as part of the data collection report in Appendix A.

Winter 2006 Sampling Data

Results for P flux for the Winter 2006 sampling effort resulted primarily in negative values for P flux, both for aerobic and anaerobic conditions. A negative value of P flux indicates phosphorus was moving from water column into the sediment. P flux measurements for anaerobic conditions were generally higher in value (less negative) than those for aerobic conditions. Although some difference in P flux values was observed between samples collected from impoundments versus riverine locations, only four riverine locations were sampled, therefore not enough samples to determine significance.

A summary of data from the Winter 2006 P flux measurements, including the range of values for P flux, is included in Table 3-3. Table 3-4 includes all P flux values for each sample location for both aerobic and anaerobic conditions.

Table 3-3. Summary of Winter 2006 P Flux Sampling Data

Location	P Flux Rate[1] (mg/m2/d) (range)	Oxidation state	Temperature
Study Impoundments	-156 to -35	Aerobic	23 C
Study Impoundments	-87 to 0	Anaerobic	23 C
Riverine Locations	-70 to -17	Aerobic	23 C
Riverine Locations	-52 to 35	Anaerobic	23 C

1) Daily rates after 24 hours.

Comparison to Previous Data

P flux rates observed during the Winter 2006 sampling effort vary significantly from previous observations, which can be attributed to numerous factors. Analyses indicate data were representative of field conditions during the time when samples were collected.

Previous sampling efforts for the Assabet River (ENSR, 2000) primarily observed spring conditions for P flux, even though temperature control was used in the laboratory to simulate winter conditions. The impact of biological activity on the Winter 2006 P flux rates was evaluated, among other potential factors.

Phosphorus Flux Rates, ENSR, 2000

ENSR conducted surveys of nutrient flux in March and September 2000. The results are summarized in Table 3-5. Negative values for P flux rates were observed for the March 2000 sample data, for aerobic conditions, under 10C.

Table 3-4. All Observations, Winter 2006 P Flux Sampling Data.

Sample ID	**Impoundment**	**P flux (mg/m2/d) daily rates after 24 hrs**	
		aerobic	anaerobic
A11	A1 Dam	52	191
A12	A1 Dam	87	-17
A13	A1 Dam	-52	-52
avg		**29**	**41**
AC1	Aluminum City Dam	-87	-17
AC2	Aluminum City Dam	-52	-70
AC3	Aluminum City Dam	0	-17
avg		**-46**	**-35**
AS1	Allen Street Dam	-243	-157
AS2	Allen Street Dam	-122	-70
AS3	Allen Street Dam	-104	-35
avg		**-156**	**-87**
R85H1	Route 85 Dam	-157	-104
R85H2	Route 85 Dam	-70	-52
R85H3	Route 85 Dam	-104	-52
avg		**-110**	**-69**
GL1	Gleasondale Dam	-17	-70
GL2	Gleasondale Dam	-87	-104
GL3	Gleasondale Dam	0	-17
avg		**-35**	**-64**
BS1	Ben Smith Dam	-122	17
BS2	Ben Smith Dam	-52	17
BS3	Ben Smith Dam	-87	-35
avg		**-87**	**0**
PM1	Powdermill Dam	-104	-35
PM2	Powdermill Dam	-52	35
PM3	Powdermill Dam	-139	-104
avg		**-98**	**-35**
	Riverine Locations		
S2	D/S of Allen Street Dam	-70	-35
S4	D/S of Gleasondale Dam	-70	-52
S6	D/S of Powdermill Dam	-17	35
S7	Nashoba Brook	-70	-52

Table 3-5. Summary of Phosphorus Flux Rates, ENSR (2000) Sampling Data

(Source: SuAsCo Watershed Assabet River TMDL Study, Phase One: Assessment, Final Report, ENSR International, November 2001).

Date	P Flux Rate (mg/m2/d)[1]	Oxidation state	Temperature
March 2000	-2.1	aerobic	10 C
March 2000	3.7	aerobic	18 C
March 2000	8.3	aerobic	25 C
September 2000	1.6 - 2.6	aerobic	20.1 C
September 2000	40 - 48	anaerobic	

1) Exposure time for reported rate unspecified.

According to the 2001 Phase I Final report (referenced previously, Executive Summary, page E-6) ENSR concluded the following regarding P flux rates in the Assabet River:

- Impoundment sediments appear to function as sinks for nutrients during the winter and sources of nutrients to the water column during the summer.
- The extent of sediment nutrient flux was observed to be limited indicating that sediment nutrient flux processes represent a relatively minor component of the overall Assabet River nutrient budget.

The following table summarizes the range of published literature values found for phosphorus flux rates. Many of these P flux rates are observed in lakes, therefore cannot be directly correlated.

Phosphorus Flux Rates, Various Literature Values

A review of published literature rates for various water bodies (rivers and lakes) throughout the United States was conducted. The majority of published literature on P flux rates included studies conducted in the southeastern U.S., primarily Florida. A summary of published literature values is included in Table 3-6. The time at which P flux rates were reported was also unspecified in many of these studies. Similar to the 2000 ENSR data referenced previously, a direct comparison between the P flux rates in the table below and the rates observed based on Winter 2006 sampling in the Assabet is not possible.

Table 3-6. Published Sediment-Water Dissolved Reactive Phosphorus Fluxes

Study Area	Sediment	Season	Oxidation state	P flux ($mg/m^2/d$) Min	P flux ($mg/m^2/d$) max	Reference
Everglades, FL	Peat		anaerobic	1.50	6.50	Fisher and Reddy (2001)
Indian River Lagoon, FL	Sand, mud			0.16	1.54	Reddy et al. (2001)
Kissimmee River, FL	Sand		aerobic	- 0.26	3.35	Moore et al. (1998)
Lake Kinneret, Israel			Both	0.30	8.50	Eckert and Nishri (2000)
Lake Okeechobee, FL	Littoral, sand, mud		aerobic	- 0.37	1.54	Moore et al. (1998)
Lake Pepin, MS			anaerobic aerobic	8.60 1.90	24.0 9.30	James et al. (1995)
South Bay, FL	Peat		Aerobic	0.05	0.77	Moore et al. (1998)
St. Johns River, FL	Mud		anaerobic aerobic	2.35 - 0.13	11.7 0.60	Malecki, White and Reddy (2004)
Swan-Canning Estuary, Australia	Coarse mud		anaerobic aerobic	2.00 0.50	53.0 5.40	Lavery et al. (2001)
Lake Eucha, OK		summer	anaerobic aerobic	2.5 1	5	Haggard et al. (2005)
Lake		summer		5		Hosomo and Sudo (1992)
Lake		summer	anaerobic aerobic	0.4 0.2	0.9	Isadezeh et al. (2005)
Lake (Germany)		summer		5	17	Kleeberg et al. (2001)
Lake (Germany)		summer	Both	15	45	Kleeberg et al. (2001)
Lake (Germany and Switzerland)		fall		6		Schauser et al. (2006)
Lake (Germany and Switzerland)		variable		2.5	9.3	Schauser et al. (2006)
Bay		variable		1	17	Seiki et al. (1989)
Assabet River, MA	Sand, silt	summer		0		USGS (2003)

Additional analyses were required to evaluate the applicability of the Winter 2006 phosphorus flux sampling date for use in the modeling study. A phosphorus mass balance model, described further in Section 4, was developed to simulate the sediment nutrient cycle and assist in evaluating the phosphorus exchanges within the Assabet River. The model also served useful in better understanding the variability in measured phosphorus flux data.

Section 4
Model Development

This section discusses the model development procedures for each of the four models used in this analysis.

4.1 HEC-RAS Model

This section describes procedures utilized in developing the HEC-RAS model. The initial step in development of the model included conversion of the original HEC-2 models for seven communities along the Assabet River into HEC-RAS model format and combining the seven HEC-RAS models into one seamless model. Due to the difference in model scheme as well as incomplete input data for some HEC-2 files, the converted HEC-RAS models were modified as necessary to match water surface profiles resulting from the original HEC-2 models. In addition, because the HEC-2 model did not exist for some reaches of the Assabet River, additional cross sections were surveyed (as discussed in Section 4.1.3 of this document) or created for addition into the HEC-RAS model.

4.1.1 Existing HEC-2 Models

Paper copies of the HEC-2 models were provided by USACE and FEMA, including Flood Insurance Studies (FIS) for 7 communities along the Assabet River. Detailed studies were performed for the following 7 communities: Westborough, Northborough, Berlin, Hudson, Stow, Maynard, and Concord. For several reaches of the Assabet River, however, detailed study had not been performed, and therefore, the HEC-2 model did not exist for these reaches. The reaches lacking detailed stud y include reaches between between Westborough and Northborough HEC-2 models, Northborough and Berlin HEC-2 models, and Maynard and Concord HEC-2 models.

For the HEC-2 models for each of the seven communities, the following procedures were used to convert existing HEC-2 model to HEC-RAS format.

1. The original HEC-2 model was typed into Excel spreadsheet.

2. The Excel spreadsheet was saved in *csv* format to maintain the column widths fit for the HEC-2 input data format. The file name extension was changed from *csv* to *dat*.

3. After creating a new project in the HEC-RAS model, the HEC-2 input data created in above step were imported to the HEC-RAS model.

4. By examining the converted HEC-RAS geometric data, find and correct the typos of the typed HEC-2 input data, and also complete the bridge or dam geometry data by adding any missing information. Bridge geometry data were also compared with available bridge plan drawings and were adjusted, if necessary.

5. By comparing the original HEC-2 output data with the HEC-RAS output, the differences in water surface elevation were analyzed, and if necessary, some modifications were made to the HEC-RAS model.

4.1.2 Modifications to Original HEC-2 data

Modifications made to each town's HEC-2 model are as follows.

Westborough

The last row of GR data of XS 30.791 is illegible. Therefore, GR stations and elevations of this row were estimated using the remaining GR data.

Northborough

Some cross sections/structures of the HEC-2 model were modified in the HEC-RAS model as shown in Table 4-1.

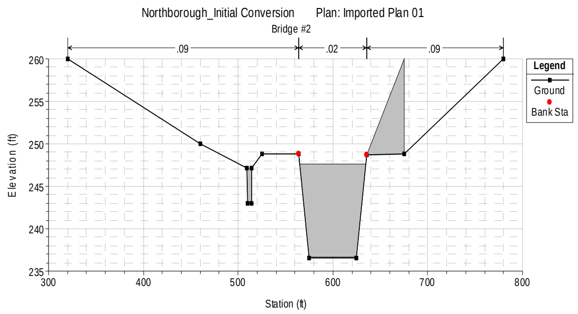
Table 4-1. Modifications to the Northborough HEC-2 Model

RAS XS or Structure Sta.	Structure Name	HEC-2 Model	HEC-RAS Model
Dams 29.2825 & 30.2325 1)	Allen Street Dam Alluminum City Dam	Bridge Structure	Inline Structure
Dam 29.2825 2)	Allen Street Dam	Bridge geometry modified	
XSs 29.352 & 28.353 3)	Cross Section	Thalweg Elev. = 239	Thalweg Elev. = 241

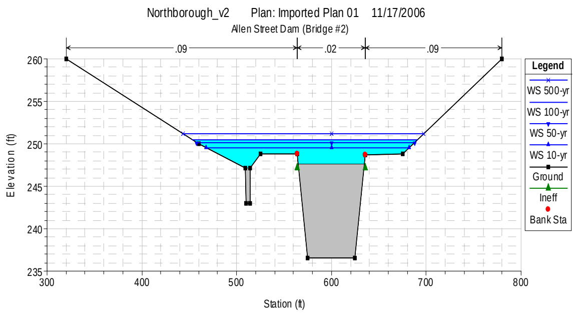
1. In the HEC-2 model, dam structure was represented by bridge structure, but in the HEC-RAS model, it was represented by inline structure.

2. The bridge geometry (BT card) of the HEC-2 model was modified as follows.

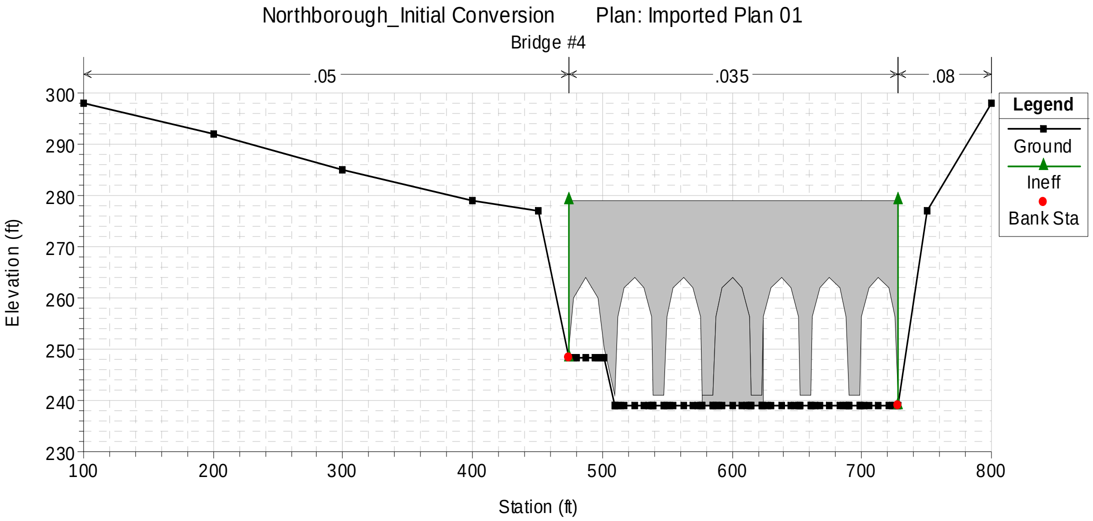
HEC-2



HEC-RAS



3. These cross sections are located immediate upstream and downstream of Wachusett Aqueduct, respectively. In the HEC-2 model, the invert elevation of these two cross sections were 2 ft lower than lower end of the bridge piers (BT card) as shown in the following plot. Therefore, stations of these two cross sections were raised by 2 ft.



Berlin

Some cross sections/structures of the HEC-2 model were modified in the HEC-RAS model as shown in Table 4-2.

Table 4-2. Modifications to the Berlin HEC-2 Model

RAS XS or Structure Sta.	Structure Name	HEC-2 Model	HEC-RAS Model
Bridge 25.6225 1)	Bridge Road	BT Station 500 BT Station 600 BT Station 700	BT Station 1500 BT Station 1600 BT Station 1700

1. Bridge stations (BT stations) of the HEC-2 model were adjusted to locate the bridge structure within the main channel.

Hudson

Some cross sections/structures of the HEC-2 model were modified in the HEC-RAS model as shown in Table 4-3.

Table 4-3. Modifications to the Hudson HEC-2 Model

RAS XS or Structure Sta.	Structure Name	HEC-2 Model	HEC-RAS Model
XS 15.2 1)	Cross Section	GR Elevation 2120	GR Elevation 212
XS 16.412 1)	Cross Section	GR Elevation 2080	GR Elevation 208
XSs 16.412 & 16.413 1)	Cross Section	GR Station 6800 GR Station 9000	GR Station 680 GR Station 900
Dam 17.9625 2)	Hudson Dam	Bridge Structure	Inline Structure
XS 18.493 1)	Cross Section	GR Elevation 1217.7	GR Elevation 217.7
Bridge 19.3125 3)	Chapin Road	BT Station 500 BT Station 600 BT Station 700	GR Station 1500 GR Station 1600 GR Station 1700
Bridge 20.3525 3)	I-495	BT Station 500 BT Station 600 BT Station 700	GR Station 1500 GR Station 1600 GR Station 1700

1. Errors occurred during the scanning process and were corrected.
2. In the HEC-2 model, dam structure was represented by bridge structure, but in the HEC-RAS model, it was represented by inline structure.
3. Bridge stations (BT stations) of the HEC-2 model were adjusted to locate the bridge structure within the main channel.

Stow

Some cross sections/structures of the HEC-2 model were modified in the HEC-RAS model as shown in Table 4-4.

Table 4-4. Modifications to the Stow HEC-2 Model

RAS XS or Structure Sta.	Structure Name	HEC-2 Model	HEC-RAS Model
Dam 14.1225 1)	Gleasondale Dam	Bridge Structure	Inline Structure
XS 15.21 2)	Cross Section	GR Elevation 2120	GR Elevation 212

1. In the HEC-2 model, dam structure was represented by bridge structure, but in the HEC-RAS model, it was represented by inline structure.
2. Errors occurred during the scanning process and were corrected.

Maynard

Some cross sections/structures of the HEC-2 model were modified in the HEC-RAS model as shown in Table 4-5.

Table 4-5. Modifications to the Maynard HEC-2 Model

RAS XS or Structure Sta.	Structure Name	HEC-2 Model	HEC-RAS Model
Bridge 7.363 1)	Waltham Street	BT Station 300 BT Station 600 BT Station 700	BT Station 1300 BT Station 1600 BT Station 1700
XS 7.441 2)	Cross Section	GR Elevation 1576	BT Station 157.6
Bridge 7.463 1)	Main Street	BT Station 500 BT Station 600 BT Station 700	BT Station 1500 BT Station 1600 BT Station 1700
Dam 8.4125 3)	Ben Smith Dam	Bridge Structure	Inline Structure

1. Bridge stations (BT stations) of the HEC-2 model were adjusted to locate the bridge structure within the main channel.
2. Errors occurred during the scanning process and were corrected.
3. In the HEC-2 model, dam structure was represented by bridge structure, but in the HEC-RAS model, it was represented by inline structure.

Concord

Some cross sections/structures of the HEC-2 model were modified in the HEC-RAS model as shown in Table 4-6.

Table 4-6. Modifications made to the Concord HEC-2 Model

RAS XS or Structure Sta.	Structure Name	HEC-2 Model	HEC-RAS Model
Dam 93.95 1)	Damonmill Dam	Bridge Structure	Inline Structure

3. In the HEC-2 model, dam structure was represented by bridge structure, but in the HEC-RAS model, it was represented by inline structure.

4.1.3 New River Stations

Prior to combining the seven HEC-RAS models for each community into one model, river stations used in the original HEC-2 models were adjusted. First, from the GIS map, locations of HEC-2 cross sections were identified. New river stations were assigned using river miles to the HEC-RAS cross sections, assuming that the river station of most downstream cross section of Concord HEC-RAS model as zero. The new river stations are included in Appendix C.

4.1.4 Additional Data

Additional data was necessary to complete development of the combined HEC-RAS model for the Assabet River. Additional data were collected via the following methods:

- Bridge and structure field verification
- Cross section surveys
- Creation of additional cross sections using HEC-GeoRAS and USGS bathymetry data

Additional information the data collection efforts, such as bridge and structure verification and cross section surveys, was discussed in Section 3.0 of this document. Based on the field reconnaissance data, dam, bridge and cross section geometry data of the HEC-RAS model were verified and if necessary, adjusted.

Additional cross sections were also created using HEC-GeoRAS in conjunction with USGS bathymetry data. After creating cross sections from a Digital Terrain Model (DTM) using HEC-GeoRAS, these cross sections were combined with the USGS bathymetry data to represent cross section geometry below the normal water surface. Where the USGS bathymetry data did not exist, only HEC-GeoRAS cross sections were added to the HEC-RAS model.

4.1.5 Model Comparison

The 100-yr water surface profile of the combined HEC-RAS model was compared to that of the original HEC-2 model. The 100-yr water surface elevations of these two models matched relatively well, except for several cross sections immediately upstream or downstream of dams or bridges. Often, the water surface elevations for these cross sections exhibited significant increases or decreases in water surface elevation between the two models.

Most of these differences were attributed to the difference in the structure modeling scheme between HEC-2 and HEC-RAS models, because these differences did not propagate into upstream cross section. Most of cross sections and structures of the HEC-RAS model were updated using field data collection in 2006, as discussed in Section 3.0 of this document. The differences in water surface elevations between the two models did not affect the results of this study.

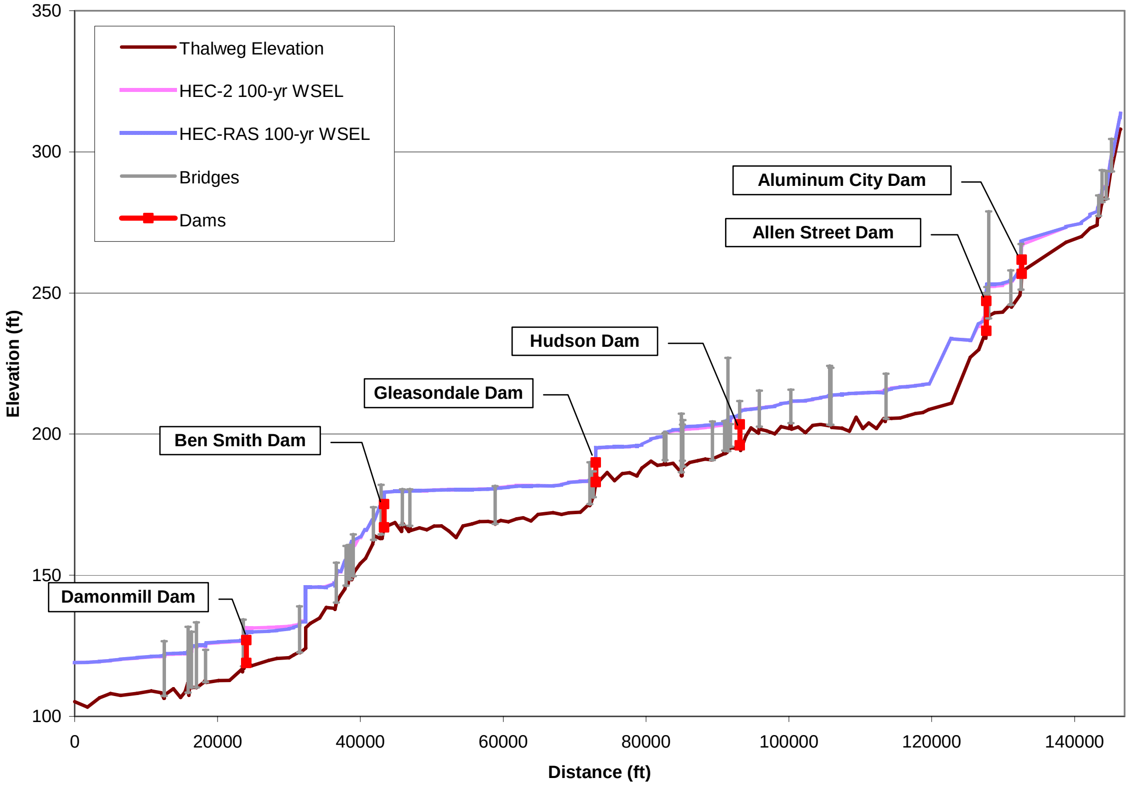


Figure 4-1. HEC-2 and HEC-RAS output comparison

4.1.6 Model Flows

The HEC-RAS model was run for 4 flow data sets, including 7Q10, average summer, 10-yr, and 100-yr flows. The 7Q10 is defined as the minimum streamflow that occurs over 7 consecutive days and has a 10-year recurrence interval period. Daily streamflows in the 7Q10 range are general indicators of prevalent drought conditions which normally cover large areas.

Two USGS gages are located on the Assabet River within the study area; at Maynard (ID 01097000) and at Mill Road (ID 010965995). The Maynard gage is situated between Ben Smith and Powdermill Dams and has a contributing drainage area of 116 square miles. The Mill Road gage is located at the upstream end of the study reach in Westborough and has a drainage area of 6.6 square miles. The Maynard gage records extend from 1941 to present. The Mill Road gage records, however, only began in July 2006.

The 10-yr and 100-yr flows were obtained from the original HEC-2 model. The 7Q10 at the Maynard stream gage (15.1 cfs) was obtained from ENSR's TMDL report (2001). The 7Q10 flow at other flow change locations were calculated using peak flow ratios. Peak flow ratios relative to the flow at the cross section closest to Maynard stream gage (RS 8.5423) were calculated from the 100-yr flows from the original HEC-2 model.

The average summer flow (66 cfs) was calculated from the July, August, and September USGS flow records at the Maynard gage (from 1941 to 2006). Average summer flows at other flow change locations were also calculated using the peak flow ratios.

Flows used in the HEC-RAS model are summarized in Table 4-7.

Table 4-7 HEC-RAS Flow Data

River Station	Flows (cfs)				
	100-yr	Peak Flow Ratio	10-yr	7Q10	Summer average
32.314	736	0.22	392	3.3	13.5
26.809	1732	0.52	820	7.9	31.8
26.5146	1850	0.56	860	8.4	34.0
20.1874	1935	0.58	888	8.8	35.6
18.3418	1998	0.60	927	9.1	36.7
17.8168	2120	0.64	974	9.6	39.0
17.6132	2380	0.72	1090	10.8	43.7
17.293	2510	0.76	1150	11.4	46.1
16.0385	2520	0.76	1153	11.5	46.3
15.3151	2664	0.80	1221	12.1	48.9
14.0893	2670	0.80	1223	12.1	49.1
12.6943	3030	0.91	1386	13.8	55.7
12.1261	3250	0.98	1486	14.8	59.7
9.5496	3250	0.98	1580	14.8	59.7
8.8174	3290	0.99	1580	15.0	60.4
Maynard - 8.5423	3320	1.00	1600	15.1	61.0
6.1271	3323	1.00	1598	15.1	61.1
4.5513	3988	1.20	1980	18.1	73.3
2.6214	4160	1.25	1975	18.9	76.4

4.2 HEC-6 Model

The HEC-6 model was used to simulate the river geometry change due to the sediment and dam removal scenarios. HEC-6 was developed by the Hydrologic Engineering Center (HEC) of the USACE to simulate a long-term average pattern of scour and deposition in rivers and reservoirs (HEC, 1993). The model input data includes geometric, hydrologic and sediment data.

4.2.1 Geometric Data

Geometric data required for input into the HEC-6 model include cross section geometry, reach lengths, and Manning’s roughness and expansion/contraction coefficients. This data was primarily obtained from the HEC-RAS model (described previously) by transforming the HEC-RAS geometric data into HEC-6 input file format.

HEC-6 does not have any provision to model structures such as bridges and dams; these structures were represented by cross section geometry modification to mimic the geometry of a particular structure. For example, the elevations of cross section geometry data used for bridge piers were set above the highest anticipated water surface elevation.

The depth of movable bed (i.e., the maximum scour depth) of each cross section needs to be defined in the geometric data. Based on site investigation and knowledge of local conditions, the maximum scour depth of most cross sections was set to 5 feet. However, for cross sections of a certain length of reach downstream of each dam, the maximum scour depth was set at 1 foot, since these cross sections generally consist of relatively coarser materials (gravels and cobbles) as compared to other reaches.

4.2.2 Hydrologic Data

Hydrologic data required for HEC-6 model development includes flow hydrograph and downstream flow boundary condition.

After comparison of peak discharges used in the original HEC-2 model, 6 flow change locations were selected, located on the upstream side of each of the six dams (Aluminum City, Allen Street, Hudson, Gleasondale, Ben Smith, and Powdermill Dams). At each of these flow change locations, daily flows were calculated using the USGS gage records and drainage area ratios.

To predict the river geometry change for a period representative of the entire flow regime, a 21 year period of data was selected, from January 1, 1986 to December 31, 2006. Although the low flows for this period are slightly higher than for the full record set, the difference was not found to be significant.

In addition to the flow records for the two gages on the Assabet River (Maynard and Mill Pond) discussed previously in Section 4.1.5, flow records from ten additional USGS gages located within or near the Assabet River study area were reviewed. Flow records were extended using Maintenance of Variance Extension Method, Type 1 (MOVE.1), based on the Maynard flow record. The intent of this method of record extension is to produce a time series that is longer than the original data series yet maintains the statistical characteristics of the record. MOVE.1 is a historically based method and focuses on preserving the sample mean and variance.

The gages exhibiting the best correlation to the flows at Maynard consisted of the following:

- Quinsigamond River at North Grafton (ID 01110000)
- Boulder Brook at East Bolton (ID 01096910)
- Nashoba Brook near Acton (ID 01097300)

The Nashoba Brook and Maynard gages were selected as the basis for the flow series for the HEC-6 modeling. Figure 4-2 shows the comparison of the hydrographs of these gages. Both gages are located within the Assabet River study area watershed and their contributing drainage areas are characterized by similar land use distributions. While Maynard reflects a larger drainage area (116 square miles), Nashoba Brook only represents 12.8 square miles.

Flows at each flow change location were developed by applying drainage area ratios relative to both the Maynard and Nashoba Brook flow records in order to generate 21-year daily flow series for each drainage area. The base Maynard flows were obtained directly from USGS. The Nashoba Brook flow records, however, covered most of the modeling period, from 1986 to September 2005 but had to be extended thereafter from September 2005 through December 2006 using MOVE.1.

No significant difference in land use distribution was observed between these two drainage areas, therefore the flow records obtained for each drainage area based on Maynard and Nashoba were averaged. Figure 4-3 shows the comparison of the hydrographs for the six flow change locations during 1986.

The HEC-6 model treats a continuous hydrograph as a sequence of discrete steady flows, each having a specified duration or time step. Although daily flow data were used as the flow hydrograph, 0.2 day was used as a time step by dividing each daily flow by 5 constant periods to increase the model stability.

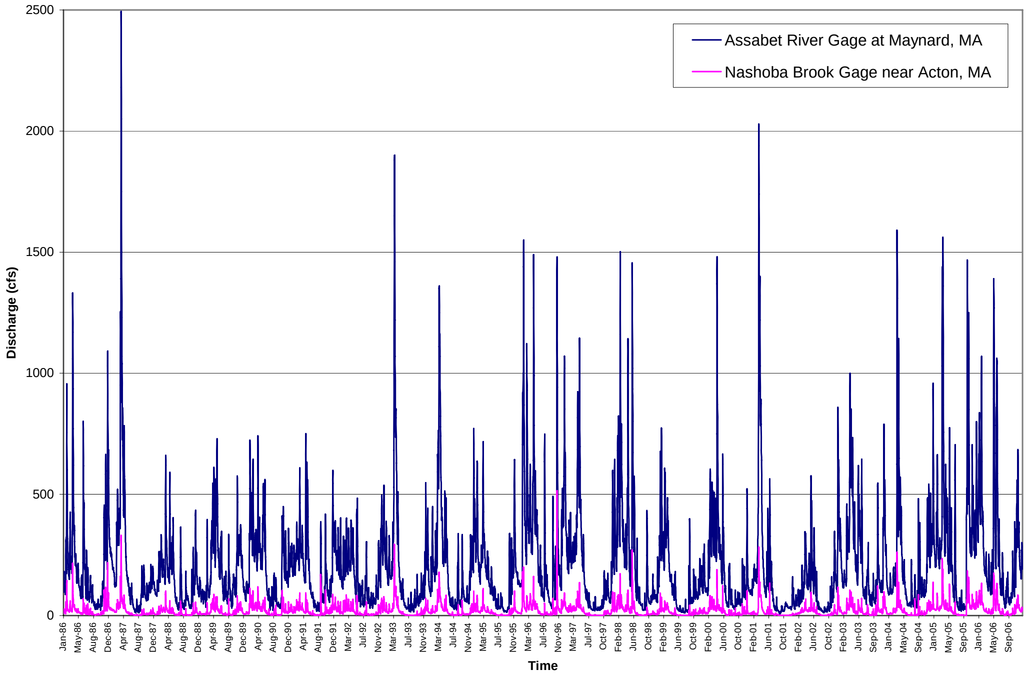


Figure 4-2. Hydrograph Comparison at two selected gages

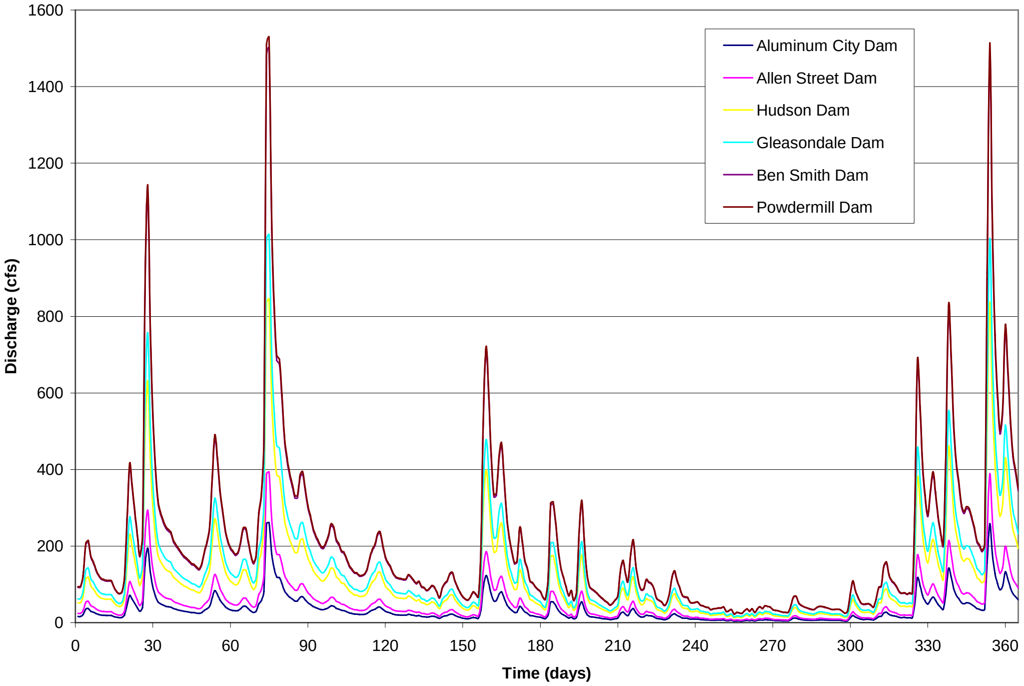


Figure 4-3. Hydrograph Comparison, 6 flow change locations, 1986

A rating curve was used for the downstream boundary condition. The rating curve at the downstream boundary was calculated from the HEC-RAS model.

4.2.3 Sediment Data

Sediment data input required for the HEC-6 model consist of the bed material gradation and inflowing sediment load data.

4.2.3.1 Bed Material Gradation

Bed material gradation data was obtained from the grain size distribution analysis for both the sediment samples collected in December 2006 and the USGS sediment cores obtained in 2003. As discussed previously in Section 3.0 of this document, in general, the grain size distribution results indicated that the Assabet River sediment consists of a mix of sand and silt, with trace amounts of clay. Gravel was found at select locations with one riverine sample (S5) classified as gravel.

4.2.3.2 Inflowing Sediment Loads

The inflowing sediment entering the upstream boundaries in the HEC-6 model are called inflowing sediment loads, expressed in tons per day. The inflowing sediment loads were calculated based on the assumption of stable channel, meaning that the inflowing sediment loads are the same as the sediment transport capacity of the cross section at upstream boundary.

The sediment transport capacity at the upstream boundary cross section was calculated using the program SAM, developed by the Coastal and Hydraulics Laboratory (CHL) of the USACE Engineering Research and Development Center (ERDC) (Thomas et al., 2002). The inflowing sediment loads at the flow change locations were also calculated.

The SAM program provides the sediment transport capacities of sand and gravel size classes only. Sediment transport capacities of clay and silt size classes were calculated by prorating the total amount of sediment transport calculated from the SAM using the fine material gradation of the impoundment samples.

4.2.4 Confirmation of HEC-6 Model Performance

Prior to conducting HEC-6 model runs, the performance of the model was confirmed using the USGS stream flow measurements at Maynard.

Using the USGS flow measurement data at the Maynard gage, the stage-discharge rating curves were constructed for two different periods (1984-1987 and 2004-2007), as shown in Figure 4-4. The measured data points and regression lines show that the gage height increased for the same discharges, especially for higher discharges. At the Maynard gage, 10-year peak discharge is 1,600 cfs and 100-year discharge is 3,320 cfs. For the discharge of 1,470 cfs, which is close to 10-year peak discharge, the measured gage height of 1984-1987 rating curve is 6.09 ft, and that of 2004-2007 rating curve is

5.44 ft, as shown in Figure 4-4. The difference is 0.65 ft, which can be considered approximately as the amount of channel bed degradation.

The HEC-6 model run for existing conditions using the input data obtained in above sections, showed a degradation of 0.87 ft at the Maynard gage, which is located at the Waltham Street Bridge. Based on this output, HEC-6 model predicts the bed elevation change relatively well in comparison to the USGS flow measurement data.

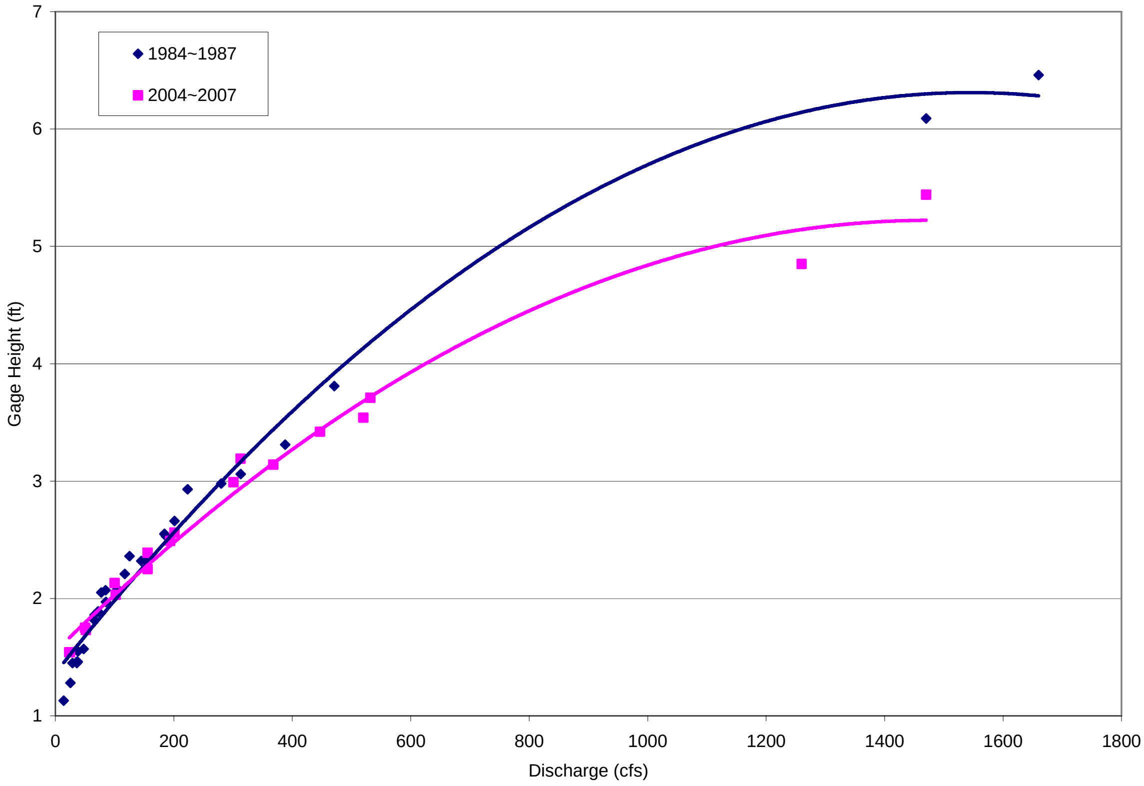


Figure 4-4. Stage-discharge rating curve comparison, Maynard gage

4.3 HSPF

4.3.1 Overview of ENSR HSPF Model

As discussed previously in Section 2, in 2005 ENSR International completed development of a water quality modeling application conducted in support of development of a Total Maximum Daily Load (TMDL) allocation for the Assabet River. ENSR calibrated the HSPF model to a set of field surveys conducted in 1999 and 2000. Calibration was focused on summertime conditions when flows are lowest and water quality tends to be the worst. The calibration time frames used in ENSR's modeling efforts were July 19-26, 1999 and Aug 28 – Sept 3, 2000. ENSR tested the model by altering boundary conditions and forcing functions and deemed it sufficient to predict ambient water quality conditions under the changing loadings that would be modeled for the purposes of the TMDL evaluation (ENSR, 2005).

ENSR evaluated a series of scenarios by changing primarily wastewater treatment facility (WWTF) effluent phosphorus loads and observing the modeled ambient phosphorus, dissolved oxygen (DO) concentrations and total biomass. Model results indicated that reduction of the WWTF effluent phosphorus concentration has the greatest effect on predicted in-stream phosphorus concentrations during summertime conditions. Additionally, sediment phosphorus flux becomes a much larger and more important component of the total phosphorus budget once WWTP phosphorus loadings are reduced. ENSR identified four alternative management scenarios that met the DO measurement standard and met other qualitative nutrient concentration standards to varying degrees. These alternatives show that only phosphorus reductions in WWTP effluent and sediment flux would achieve the required water quality improvements. Other modifications evaluated were not sufficient to realize the required water quality levels.

ENSR recognized that as modeled conditions diverge from existing conditions, the uncertainty of the model results increases. They recommended that as nutrient concentrations change, for example, by a factor of ten, it would be appropriate to examine the validity of model results and adjust various parameters as needed to reflect the new existing water quality characteristics of the river.

4.3.2 ENSR HSPF Model Provided to CDM (CDM Baseline Model)

CDM received the Assabet River HSPF model files from ENSR that were understood to be the calibrated model files. The model files consisted of a user input file (*.uci) and a file containing multiple time series (*.wdm). The UCI file contains several user input parameters, model schematic and linkages between reaches, pervious and impervious land data and output control. The WDM file contains time series of input and output data, such as precipitation, sunlight, gaged flow, WWTP flows and mass loadings, modeled flow and other data.

During the quality assurance process, CDM ran the HSPF model provided by ENSR to confirm that the results reported in the ENSR final report could be reproduced and serve as a baseline before modifying hydraulic conditions on the river. This model will be referred to as the CDM baseline model. Results from the ENSR report were used to compare with CDM baseline model results are summarized below. The results of model comparison are included in Appendix D.

Data used to produce the results in the ENSR final report were not supplied to CDM. However, comparison of the CDM baseline model results to the summary of results included in the ENSR report resulted in the following conclusions:

- Modeled flows at the USGS Maynard gage were generally better calibrated to observed flows in the CDM baseline model than in the ENSR final report and are generally higher than flows presented in the ENSR report. The largest differences are seen during the late summer months.

- Water quality data was generally a very good match. The largest discrepancies between the CDM baseline model and the ENSR results were the maximum and minimum values of nitrate and orthophosphorus. The CDM baseline model output used daily values, whereas the ENSR values could have been hourly minimum and maximum values. The average values differ slightly in magnitude, but overall are a good match to the results presented in the ENSR report.

- The CDM baseline model has hourly output for DO and the minimum and maximum values align better with the ENSR reported values than the nitrate and phosphorus.

- Flows at the WWTPs in the CDM baseline model were within 5% of flows reported in the ENSR report.

- Phosphorus mass loadings at the WWTPs in the CDM model differed from those values reported by ENSR by less than 5% approximately 75% of the time. Mass loadings differed significantly during July, August and September, and at the Hudson WWTP for most of the reported values. ENSR reports in the water quality calibration section that during the calibration and validation time frames, daily values of phosphorus were adjusted from the monthly values because modeled values did not correspond to daily field measurements. These changes may account for the discrepancy at all but the Hudson plant and are not reflected.

- Phosphorus mass loadings at the WWTP were analyzed to see if they fit the profile of a given scenario run by ENSR as part of their alternative analysis or if mass loadings were based on WWTP permitted flows used in the ENSR model. However, the mass loadings did not correspond to any of the named scenarios or the permitted flows.

- Overall, the CDM baseline model is likely not identical to the ENSR model in the report. Water quality data is very similar, and flows and mass loadings at the WWTPs are close to reported values (though not exactly the same values) indicating the CDM model baseline will behave in similar manner to the ENSR final report model.

4.3.3 Modifications to the CDM Baseline Model

The CDM baseline model was modified to incorporate updated hydraulics represented by the HEC-6 and HEC-RAS modeling results. The model was also modified to incorporate different sediment phosphorus flux rates based on the separate phosphorus flux modeling analysis.

4.3.3.1 F-Tables

HSPF models the hydraulics of a river through a series of tables called F-Tables (function tables). Every reach within the model is linked to a specific F-Table which defines the hydraulics for the specific reach. Average depth, surface area, volume and outflow are tabulated in each F-Table, and the model accesses the hydraulic parameter required through linear interpolation of the F-Table values. Thus, F-Tables that areF more finely discretized introduce less error in representing a non-linear system.

The CDM baseline model contains 30 F-Tables, corresponding to the 30 reaches in the model. There are 9 flow levels tabulated in the majority of the F-Tables, though a few have only 2 flow levels. Hydraulic data from the HEC-RAS modeling was aggregated into the 30 HSPF reaches to incorporate the new hydraulics into the model.

Update Procedure

The HSPF model is configured to function with the 30 reaches defined in baseline model. During the HEC-RAS modeling, the river was discretized into several hundred reaches. F-Tables were generated through the HEC models for 12 different flow levels, the lowest flows being 7Q10 flow level, and highest being the 100-year event. The F-Tables produced for each HEC reach were aggregated into the 30 HSPF reaches, the model input files were updated and the effect of the updated river hydraulics was evaluated.

The aggregation of hydraulic parameters was achieved by applying a length-weighted average to determine average depth and flow and summing surface area and volume. The aggregation of HEC-RAS reaches into aggregated into HSPF reaches is shown in Appendix D, Figure D-17. Depth and flow were assumed to be valid from midpoint to midpoint between the HEC cross sections. The distance between midpoints is considered a HEC-RAS reach. Where a HEC-RAS reach overlapped an HSPF boundary, the HEC-RAS values were used only if the HEC-RAS cross section fell within the HSPF reach. If the HEC-RAS cross section fell outside of the HSPF boundary, the values at the next adjacent HEC-RAS cross section falling inside the HSPF reach were then extended to the HSPF reach boundary. Weights for each HEC- RAS reach were calculated as the proportion of the HEC-RAS length to the HSPF length.

Surface area and volume are additive parameters. Volume and surface area are calculated from cross-section to cross section in HEC-RAS and are therefore treated differently than depth and flow. The HSPF reach surface area and volume were calculated by summing the surface area and volumes of the HEC-RAS reaches that fell within the HSPF reach. In the case of overlapping sections, the amount proportional to the length within the HSPF reach was used in the sum. Once new aggregate values of the hydraulic parameters were calculated, new F-Tables using the 12 flow levels from the HEC output were generated, formatted for model input, and were inserted in the HSPF model file in place of the original F-Tables.

Hydraulics Using New F-Tables

The hydraulics of the river were evaluated prior to any model runs to identify locations of largest changes and to evaluate how well the aggregation technique matched the HEC-RAS modeling. Mean cross sectional area, velocity and travel time were computed from the F-Tables using the following relationships:

Mean Cross Sectional Area = Volume / Mean Depth
Mean Velocity = Flow Rate (Q) / Mean CrossSectionalArea
Mean Travel Time = Mean Velocity * Reach Length

The cumulative travel time, cumulative volume and average depth at 7Q10 flow, respectively are shown in Appendix D, Figures D-18 through D-20. The aggregated F-Tables mimic the HEC-RAS modeling results quite well. Additionally, the most prominent difference in river hydraulics occurs at the Elizabeth Brook reach, which is immediately upstream of the Ben Smith dam. Residence time increases significantly and consequently mean velocity is much lower than in the baseline model. While the mean depth values of the aggregated F-Tables do not capture the finer discretization of the HEC-RAS model as well, in the area near Elizabeth Brook (approximately miles 19 – 23 on Figure D-20), the aggregated F-Tables mean depth increases with the HEC model results. The increased resolution provided by the HEC-RAS model for this reach provides a more accurate representation of this reach in the HSPF model, also illustrated in the plot of flow versus volume (Figure D-21). Simulated water quality is expected to change most significantly in this area compared to ENSR model ouput, since hydraulics were modified significantly in this reach.

Water Quality Using New F-Tables

The F-Tables in the CDM baseline model files were replaced with the new F-Tables and the model was run to assess the impacts of the new hydraulics on water quality. In particular, the calibration and validation time periods used by ENSR were examined (August 28 – September 3, 2000 and July 19-26, 1999). Several water quality parameters can be output from the model, including concentrations of orthophosphorus, nitrate, dissolved oxygen (DO), ammonia, phytoplankton, and benthic algae. Simulated concentrations of orthophosphorus comparing the new F-Tables to the CDM baseline for 1999 simulation period are shown in Figure D-22. Both weeks were periods of low flow in the river; in 2000 the average flow for the week was 36 cfs, in 1999 average flow was 16.5 cfs measured at the Maynard gage. The model overpredicts these flows with both the CDM baseline and the new F-Tables; simulated flow for 2000 was 54 cfs and 29cfs in 1999. Orthophosphorus (PO4) concentrations increase significantly in 1999 in the Elizabeth Brook reach compared to the CDM baseline, while this does not occur in 2000. The reason behind the phosphorus spike in 1999 was evaluated and details of this evaluation are discussed below.

Simulated dissolved oxygen concentrations for the calibration weeks in 2000 and 1999 are shown in Figures D-23 and D-24, respectively. These plots also show the hourly minimum value of DO at several points along the river. The weekly average nitrate concentrations for the calibration weeks in 2000 and 1999 are shown in Figures D-25 and D-26, respectively. Nitrate concentrations do not change significantly between the baseline simulation and the new F-Tables. There is a drop in nitrate concentration at the same location as the Orthophosphate (as P) spike in 1999, as shown in Figure D-26. This was evaluated to determine if nitrate concentration was limiting the growth of phytoplankton in the river. The growth is somewhat limited, but not sufficient to cause the Orthophosphate (as P) spike, especially when considering the phytoplankton were modeled to metabolize ammonia when there is a shortage of nitrate.

Although residence time will increase in the impoundment in the Elizabeth Brook reach in 1999 due to lower flows and velocity, the spike in 1999 is not due to hydraulic residence time changes. For a given flow rate, hydraulic changes alone will not cause a jump in concentration. Even though the residence time is greater, and the exposure time to the sediment phosphorus loading is greater (and thus total mass in the reach is greater), the dilution volume is also greater and therefore the concentration will not be affected.

The surface areas in the Elizabeth Brook and Ben Smith reaches for the new F-Tables are only about 5% greater than the original F-Tables. Since surface area does not increase significantly, neither does the bottom area where sediment phosphorus is released into the river. Therefore, the change in surface area, and the resulting change in sediment phosphorus flux loading appears to account for only a small portion of the simulated Orthophosphate (as P) spike seen in 1999.

The simulated biology of the system also appears to only account for a relatively small portion of the spike. Sensitivity analyses were performed, looking at how the Orthophosphate (as P) profiles change with differences in simulated phytoplankton. Phytoplankton concentration was held constant and the Orthophosphate (as P) profiles were compared for both the baseline and new F-Table scenarios in 1999. The model is sensitive to phytoplankton growth, but not enough to explain the entire PO4 spike. Figures D-27 and D-28 show the results of the model runs with phytoplankton population held constant and simulated and the resulting Orthophosphate (as P) profiles. The plots show that when phytoplankton is maintained through the downstream reaches (rather than allowing it to fall to almost zero) for the new F-table simulation, the Orthophosphate (as P) spike does decrease but, again, not enough to be the entire explanation. It is also important to note that benthic algae basically disappears in the downstream reaches for the new F-Table simulation (and was very high for the baseline run). This is expected, as depth has been increased considerably in this reach, and probably also makes a small contribution to the Orthophosphate (as P) spike.

The primary cause of the Orthophosphate (as P) spike in 1999 appears to be the difference between model anaerobic and aerobic sediment phosphorus flux rates. For the summer 1999 simulation with new F-Tables, DO concentrations actually fall below the input anaerobic threshold (0.001 mg/l) in Elizabeth Brook (Figure D-24), including just prior to the July 19-26 calibration period. The sediment phosphorus flux rate for anaerobic conditions is an order of magnitude higher than under aerobic conditions (200 vs. 20 mg/m^2/d). During anaerobic conditions, the phosphorus loadings increase considerably. In the baseline simulation, the system never becomes anaerobic during the summer of 1999. This reach of the river does not become anaerobic in summer 2000, whether modeled with the baseline or with the new F-Tables (Figure D-23).

Time series of Orthophosphate (as P) concentrations in the summer of 1999 and 2000 are shown in Figures D-29 and D-30, respectively. Anaerobic conditions are marked on these plots. In Figure D-29, it is clear that Orthophosphate (as P) concentrations increase rapidly once the river becomes anaerobic. This reach experiences anaerobic conditions for the 7 days before the calibration week in the summer of 1999, which explains why the phosphorus is so high in 1999. Since the river reach does not experience anaerobic conditions in the summer of 2000, the Orthophosphate (as P) levels do not increase significantly as in 1999.

In summary, the updated F-Tables did not result in significant differences in modeled water quality as compared to either the ENSR model or the CDM baseline model, with the exception of DO limiting conditions.

4.4 Phosphorus Flux Model

In HSPF, sediment nutrient fluxes are specified as constant values by the user, and vary only with the level of oxygenation in the overlying water column. The HSPF model does not simulate the dynamic sediment nutrient cycle, in which phosphorus settles and diffuses into the soil, partitions between particulate and dissolved phases, accumulates or depletes, and returns to the water column via pore water diffusion. Monitoring results suggest that nutrient flux rates, and even the prevailing direction into or out of the sediment, can exhibit considerable seasonal variability. The HSPF model is useful for examining the influence of specific constant flux rates on water quality, but it does not account for the dependency of sediment fluxes on settling loads or overlying water column phosphorus concentrations.

A steady state phosphorus mass balance model (referred to herein as the P flux model) was developed to simulate the sediment nutrient cycle and assist in evaluating the phosphorus exchanges within the Assabet River. By varying overlying concentrations and settling rates, the model was useful in better understanding the variability in measured data, as well as the likely responsiveness of the sediment flux to future river management alternatives. The P flux model was developed using equations extracted from USEPA's QUAL2K river and stream water quality simulation computer model (Chapra, S.C., Pelletier, G.J. and Tao, H. 2006), using its formulations for inorganic phosphorus. The phosphorus equations that were extracted were originally based on a model developed by Di Toro (Di Toro et al. 1991, Di Toro and Fitzpatrick. 1993, Di Toro 2001).

The P-flux model simulates time-dependent sediment-water fluxes of phosphorus as a function of constant (steady state) settling of particulate organic matter, reactions within the sediments, and the concentrations of dissolved phosphorus in the overlying waters. The model represents the system as three layers: the water column (0), aerobic sediment layer (1) and anaerobic sediment layer (2). A schematic of the QUAL 2K model is presented in Figure 4-5.

Phosphorus enters the sediment as a result of settling of particulate organic matter (phytoplankton and detritus) from the overlying water, as depicted in Figure 4-5. The organic phosphorus is then transformed by mineralization reactions into inorganic phosphorus (diagenesis). Once in the sediment, the inorganic phosphorus partitions between the dissolved and particulate forms, and moves between the upper aerobic sediment layer and the lower anaerobic sediment layer from sediment mass transfer and pore water diffusion processes. A portion of the phosphorus exits the system through downward burial into the channel bed and is no longer available. Finally, dissolved phosphorus re-enters the water column via diffusion between the pore water and the water column at the sediment-water interface.

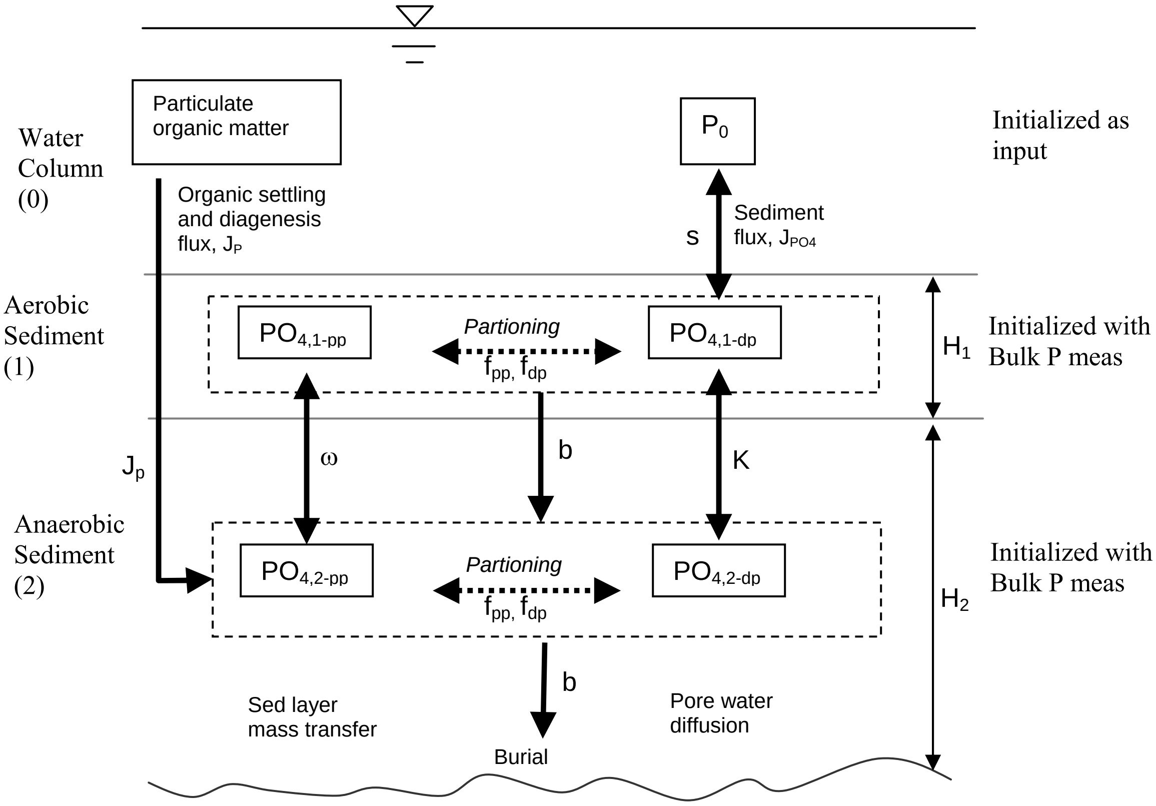


Figure 4-5. P Flux Mass Balance Model Schematic

4.4.1 P-Flux Model Formulation

The model is formulated and solved using two differential equations for the state variables of total phosphorus concentration in each of the two sediment layers. The equations, shown below, reflect the movement and transformations of phosphorus depicted in the figure above, and were extracted directly from USEPA's QUAL-2K model:

$$H_1 \frac{dPO_{4,1}}{dt} = \omega\left(f_{pp2}PO_{4,2} - f_{pp1}PO_{4,1}\right) + K\left(f_{dp2}PO_{4,2} - f_{dp1}PO_{4,1}\right) - bPO_{4,1} + s\left(\frac{p_0}{1000} - f_{dp1}PO_{4,1}\right)$$

$$H_2 \frac{dPO_{4,2}}{dt} = J_P + \omega\left(f_{pp1}PO_{4,1} - f_{pp2}PO_{4,2}\right) + K\left(f_{dp1}PO_{4,1} - f_{dp2}PO_{4,2}\right) + b\left(PO_{4,1} - PO_{4,2}\right)$$

where:

PO_4 = bulk P sediment concentration
H = sediment layer thickness
J_p = organic phosphorus settling and diagenesis
ω = mass transfer coefficient between sediment layers (for particulate P)
K = pore water diffusion coefficient (for dissolved P)
b = burial velocity
s = mass transfer coefficient between water and aerobic sediment
f_{pp} = partitioning coefficient for particulate P
f_{dp} = partitioning coefficient for dissolved P
p = dissolved inorganic phosphorus concentration in overlying water column

Numeric subscripts denote the relevant layer in the schematic diagram above. Values shown in bold are model parameters, and those in standard notation are input values or state variables.

The inorganic phosphorus flux into or out of the sediment is the last term of the first equation above, and is a function of the differential concentrations of dissolved phosphorus in the water column and the pore water of the aerobic sediment layer:

$$Flux = s\left[\frac{p_o}{1000} - f_{dp1}PO_{4,1}\right]$$

4.4.2 P-Flux Model Parameterization

Model parameters were determined largely from literature values. The partitioning coefficients were tuned slightly to reflect observed flux rates of dissolved phosphorus. The final model was based on the parameter values shown in Table 4-8.

Table 4-8: P-Flux Model Parameters and Input Values

Parameter	Description	Value	Source/Rationale
H_1	Thickness of aerobic sediment layer	0.0008 m	Calculated as H_1 = DO/s, where DO is water column dissolved oxygen. QUAL2K documentation suggests 0.001 m.
H_2	Thickness of anaerobic sediment layer	0.1 m	QUAL2K documentation
ω	mass transfer coefficient between sediment layers (for particulate P)	0.0012 m/d	DiToro, Table 6.1[1]
K	pore water diffusion coefficient (for dissolved P)	0.01 m/d	DiToro, Table 6.1[1]
b	Burial velocity	$6.85 * 10^{-6}$ m/d	DiToro, Table 6.1[1]
s	Mass transfer coefficient between water and aerobic sediment	0.243 m/d	Calculated as s = SOD/DO, where SOD = 1.944 $gO_2/m^2/d$ per Table 2-13 of ENSR 2005 modeling report, and DO = 8 mg/l as measured by ENSR and USGS (representative value)
f_{dp1}	partitioning coefficient for dissolved P in anaerobic sediment	0.0037	Chapra, Equation 40.29[2]
f_{dp2}	partitioning coefficient for dissolved P in anaerobic sediment	0.0045	Chapra, Equation 40.29[2]
f_{pp1}	partitioning coefficient for particulate P in aerobic sediment	0.9963	Calculated as $f_{pp1} = 1 - f_{dp1}$
f_{pp2}	partitioning coefficient for particulate P in anaerobic sediment	0.9955	Calculated as $f_{pp2} = 1 - f_{dp2}$

1. *DiToro, Dominic M., Sediment Flux Modeling, 2001, Table 6.1, p. 136*
2. *Chapra, Steven C., Surface Water-Quality Modeling, 1997, Eqn. 40.29, p. 709*

4.4.3 P-Flux Model Initialization

Initial values for the state variables (sediment phosphorus concentrations) were estimated from bulk phosphorus measurements reported by USGS and ENSR. For current conditions, initial values were estimated as follows:

$PO_{4,1}$ = 171 gP/m^3 total vol (aerobic)

$PO_{4,2}$ = 141 gP/m^3 total vol (anaerobic)

These values were later adjusted experimentally to simulate the potential reductions of existing sediment concentrations that might result from dredging, and the associated long-term steady state flux rates.

4.4.4 Steady State Variables

Three steady-state variables are used in the model formulation:

- J_P = Organic phosphorus load into sediment from biological matter deposition (via settling and diagenesis)
- p_0 = Inorganic phosphorus concentration in water column
- DO = dissolved oxygen level in water column

Settling values were initially estimated from the HSPF model, and experimentally adjusted to simulate the impacts of reductions in upstream treatment plant loads. Water column concentrations were determined from representative sampling data, and were also experimentally adjusted to simulate future conditions. Dissolved oxygen concentration in the water column was effectively treated as a binary variable: either aerobic or anaerobic, and this condition was used to adjust the partitioning coefficients for anaerobic conditions as necessary.

4.4.5 Model Testing

The model was tested with representative steady state variables for summer conditions, as determined from the collected sampling data and HSPF settling rates. Results are shown in Figure 4-6. The figure illustrates that the model predicts a long-term steady state flux for summertime conditions that is lower than what was used in the original HSPF model, but slightly higher than values that were measured by ENSR (suggesting that settling rates may be slightly too high).

The input values were experimentally adjusted to simulate both summer and winter conditions, and the model replicated the observed trends in the data. Specifically, during late fall and winter, the model simulated the reversal of direction of phosphorus, since reduced algal growth and subsequent settling occur in winter and higher overlying water concentrations (higher winter limits on upstream treatment plant discharges) result in higher concentrations in the water column than in the sediment pore water. Consequently, phosphorus can exhibit a net diffusion out of the water column and into the sediment under these conditions, and the model replicated that phenomena.

Results of the experimental runs that were used to examine changes in settling and water column concentration are discussed in Sections 5 and 6. Experiments were conducted both for long-term impacts of dredging, and for seasonal influences of overlying water column concentrations.

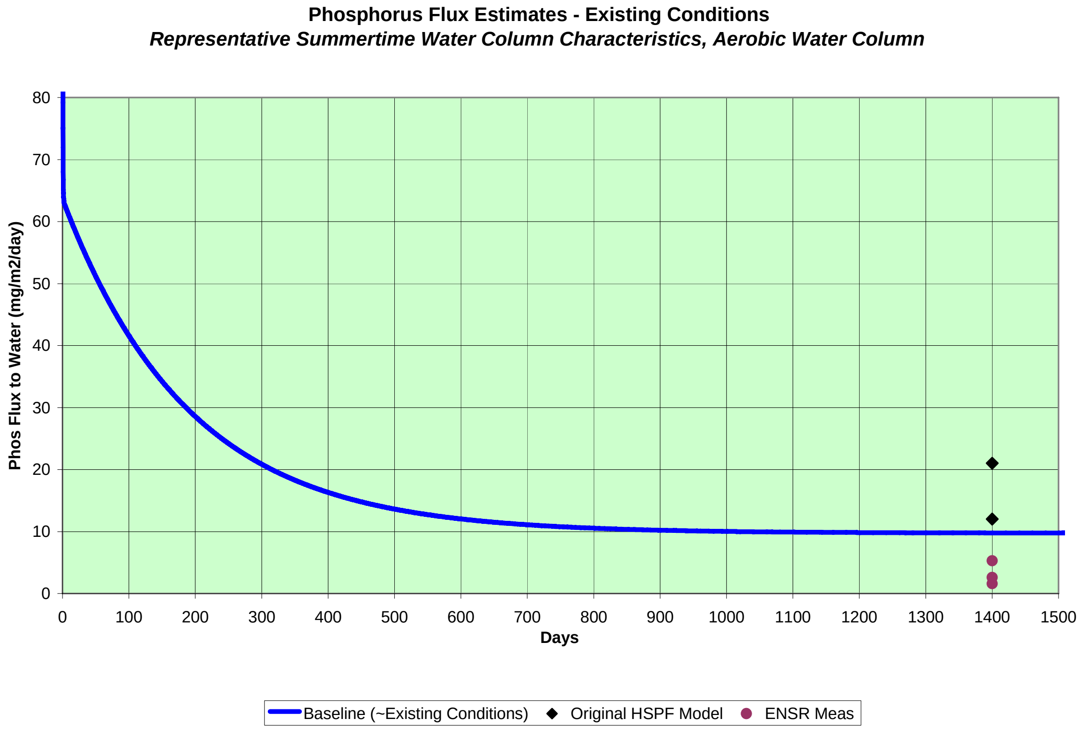


Figure 4-6: Testing of Phosphorus Flux Model for Existing Conditions

Section 5
Model Scenarios and Results

This section presents model scenarios evaluated and discusses results for each scenario, including information on sediment transport, water surface profile and water quality. Detailed results, including profiles and tables, are provided in Appendices E and F as referenced throughout this section. Models are provided are separately on CD.

5.1 Model Scenarios

As stated previously, the purpose of the modeling conducted in this study was to determine the various changes in the Assabet River from sediment and dam removal scenarios. Various scenarios were modeled, analyzed and discussed in this section. A total of seven scenarios were simulated using the suite of models. A summary of the scenarios is included in Table 5-1.

Table 5-1. Model Scenarios

Scenario	Description
Base Conditions (2000)	Existing conditions, 6 study dams in place
Planned Improvement	WWTF Phosphorus (P) reduction. This scenario assumes WWTF P discharge is 1.0 mg/L in the winter (November – March) and 0.1 mg/L in the summer months (April – October)
A	Planned improvements + Remove all 6 study dams
B	Planned improvements + Dredge sediment to a depth of 3 feet in all 6 study impoundments to reduce the phosphorus flux in the impoundments
E	Planned Improvements + Remove Gleasondale, Hudson and Ben Smith dams
H	Planned improvements + Remove Ben Smith dam
N (P flux model only)	Evaluate additional reduction in Phosphorus limit at WWTF – winter months

For each scenario, the following steps were performed:

- HEC-6 (sediment transport model) was run to obtain the new river bed profile and determine sediment movement
- HEC-RAS (water surface/hydraulic model) was run to determine the water surface profile and river hydraulics based on the revised river cross-sectional information from HEC-6, and
- HSPF (watershed and river water quality model) was run to determine the resulting water quality based on the revised hydraulic information from HEC-RAS and phosphorus sediment flux information from the P flux model.

Revisions to the HSPF model (discussed in Section 4) were required to improve the hydraulics in the HSPF model necessary to accurately represent the dams. These modifications resulted in an uncalibrated HSPF model. However, the technical group determined that the HSPF model was still a useful tool for the purpose of evaluating alternatives and their relative impacts on water quality in the river.

Scenario N, which evaluated the impact on phosphorus sediment flux from a reduction in phosphorus limits at WWTFs during the winter months, was conducted using the P flux model only.

5.2 Model Results

For each scenario identified in Table 5-1, the models were modified to reflect proposed changes of the alternatives, and model simulations were conducted. As noted above, the results of one model provide input into the next model. The models were run in a sequential manner to reflect the proposed changes of a specific scenario. The findings on sediment transport, water surface profiles and water quality for each scenario are discussed in the following sections. Detailed model results are included in Appendices E (Sediment Model/HEC-6) and Appendix F (Hydraulic Model/HEC-RAS).

5.2.1 Base Conditions (2000)

The Base Conditions represent the river in the year 2000. The Base Conditions scenario is representative of the river prior to upgrades to the WWTFs, during a time period when extensive river water quality monitoring was performed. As part of the TMDL study, it was determined that in order to achieve water quality standards, WWTF treatment discharge of phosphorus would need to be reduced to 0.1 mg/l during the summer months and the sediment phosphorus flux would need to be reduced by 90 percent. Other scenarios will be compared to base conditions to determine if the TMDL goals for phosphorus flux reduction are met with proposed changes.

Sediment Transport

The development and confirmation of the HEC-6 model of the Assabet River was presented in Section 4.2. Cross sectional data (from HEC-2 files, additional cross-sections and field observations), river flow, and sediment loading and bed gradation were used as input to develop a model that accurately simulates the sediment transport for the existing river conditions. The existing and the 20-year no-action bed profile (thalweg) for the base conditions are depicted in Appendix E, Figure E-1. This will be the basis of comparison for all other scenarios.

Water Surface Profile

Procedures used in developing an updated hydraulic model using the HEC-RAS model for the Assabet River were discussed in Section 4.1. The starting point for this effort work was the existing HEC-2 model used by FEMA to produce the Flood Insurance Studies (FIS) for each community. Additional river cross section data was collected and field observations/confirmation of the bridge information was also performed. The resulting water surface profile predicted by the updated HEC-RAS model was compared to the water surface profiles predicted in the FIS by the older HEC-2 model. Differences were investigated and primarily were the result of bridges modified since the completion of the FIS and a few errors in the older HEC-2 model. Predicted water surface profiles for the existing river condition are included in Appendix F. This will be the basis of comparison for all other scenarios.

Water Quality

The existing HSPF model was provided to CDM for application on this study. Section 4.3 provides an overview of the procedures used by CDM to confirm the accuracy of the HSPF model. CDM modified the portion of the HSPF model containing the river hydraulics, the F-Tables for purposes of this study. The F-tables were modified because the existing F-tables did not accurately represent the dams. Specifically, the water depths behind Ben Smith and other dams were significantly under represented in the existing HSPF model. The revised F-tables, based on the updated HEC-RAS model more accurately represent the water depth and travel time in the system. The predicted water quality for the updated HSPF model is included in Appendix D.

5.2.2 Planned Improvements

The planned improvements include a reduction of phosphorus to 0.1 mg/l in the discharge of the WWTFs during the summer and 1.0 mg/l during the winter (November 1 – March 31). This scenario examined the effect of the planned improvements on the sediment transport, water surface profile and water quality of the river.

Sediment Transport

This scenario produces no change in the sediment transport of the river.

Water Surface Profile

This scenario produces no change in the water surface profile from Base Conditions.

Water Quality

The planned improvements, including reduction of phosphorus discharged from the WWTFs, produce several changes to water quality. First, the lower phosphorus discharge produces lower instream concentration of phosphorus in the river. The lower phosphorus concentrations produce lower algal counts and improved dissolved oxygen. Additionally, the lower algal counts produce less algal settling which reduces the phosphorus flux from the sediment to the water column.

The reduction in limit of phosphorus discharged in WWTF effluent in the winter (1.0 mg/l) also results in a decrease summer sediment phosphorus flux. The P flux model predicted a 60 percent decrease in phosphorus sediment flux from the Planned Improvements compared to Base Conditions. The phosphorus discharged from the WWTFs during the winter had a very significant impact on the P flux the following summer. The P flux model indicated that the high P in the water column would adsorb on to the sediment material during the winter months.

During the simulation when WWTFs reduced the concentration of P discharged in the late spring, the river sediment had a high P content from the winter, and the sediment would release P back to the water column. Results of this study indicate that the high summer P flux is due to not only the algal settling and cycling through the sediment, but also the high P in the sediment from the winter conditions.

5.2.3 Remove All 6 Study Dams

This scenario examined the changes in sediment bed, water surface profile and water quality that would result from removal of the six study dams. This scenario represents restoring the river back fully to a free-flowing, riverine system. This scenario also includes the planned improvements discussed in the previous section.

Sediment Transport

Removing a dam can allow movement downstream of the sediment behind the dam. Dam removal reduces river depth and increases flow velocity in the areas behind the removed dam. The finer sediment behind the dam may move downstream because of the new, higher river velocities. The HEC-6 model was used to determine if any sediment would move downstream after dam removal, and if so, how much sediment would be transported downstream, if no preventative measures were taken (e.g. dredging associated with dam removal).

This analysis allows determination of the amount of sediment to be dredged or stabilized in place to prevent sediment transport downstream with dam removal, which will be conducted as part of ongoing study efforts. The sediment gradation under the existing dams remains an unknown factor in this evaluation. For modeling purposes, it was assumed that the sediment material under the existing dams was not readily susceptible to movement.

The river bed profile for the Base Conditions and the bed profile after 20 years with all six dams removed are shown in Appendix E, Figure E-2. As depicted in the figure, model results show that sediment transport would occur for each of the dams removed. Dredging would need to be included as part of any dam removal to minimize downstream sediment movement. Estimated volumes of sediment to be dredging with dam removal will be calculated as part of a future task of this study.

It is important to note that the simulated bed profiles are representative of long term flow conditions for the most recent 20 years (1986-2006) of flow data. The modeling scenario assumes flow conditions will be similar for the next 20 years.

Water Surface Profiles

Cross-sectional information to represent the dams in the HEC-RAS model was revised to reflect dam removal and various flow conditions simulated. The HEC-RAS model results indicate that dam removals will significantly lower the water surface elevations for the 7Q10, summer average flow, 10-year flood, and the 100-year flood flow conditions. The largest change in water surface elevation occurs for the lower flow conditions, 7Q10 and summer average flows.

The change in depth behind each of the dams for the four flow conditions is presented in Table 5-2. Water surface profiles for removing all 6 dams are included in Appendix F, Figure F-2.

Table 5-2. Change in water surface elevation for various flows scenarios. (All values in feet).

Dam	**7q10**	**Summer Average**	**10 year**	**100 year**
Aluminum City	-4.9	-4.8	-4.2	-0.6
Allen Street	-3.4	-3.5	-4.7	-5.6
Hudson	-7.0	-6.9	-5.4	-3.4
Gleasondale	-4.7	-4.5	-4.6	-5.1
Ben Smith	-7.4	-7.4	-5.6	-4.0
Powdermill	-7.8	-7.6	-7.2	-7.1

Water Quality

The water quality of the Assabet River was simulated using the HSPF model. The HSPF was modified to reflect all six dams removed using the hydraulic information from HEC-RAS to create new F-tables for HSPF. Additionally, the P flux model was used to determine the sediment phosphorus flux with all six dams removed.

The water quality significantly improved with the removal of the six study dams on. Removing a dam had multiple benefits in water quality. First, the residence time in each impoundment was reduced which reduced the biomass growth in the river. Removing the dams for the larger impoundments had the largest benefits. Removing Ben Smith dam had the largest benefit, Hudson, Gleasondale, and Powdermill dam removals had next best benefits, and Aluminum City and Allen Street had smallest benefits. A second benefit from removing dams is reduced sediment phosphorus flux from the reduced biomass growth. Reduced algal and macrophyte growth produces less algae to settle and less phosphorus cycling through the sediments. The sediment phosphorus flux reduction is expected to be approximately 80 percent, near the TMDL target of 90 percent reduction. A third benefit from dam removal is increased reaeration in the shallower water depths. Increased reaeration will improve dissolved oxygen in the river.

5.2.4 Sediment Removal/Dredging

This scenario examines the changes in sediment bed, water quality and the water surface profiles from dredging sediment behind each of the six dams. Dredging would be performed to remove the sediment material that is high in phosphorus and contributing to the P flux problems in the river. This scenario includes the planned improvements as discussed in Section 5.2.2.

Dredging/sediment removal was evaluated in the six study impoundments by modeling the effect of removing approximately three feet of sediment for the length and width of each impoundment. The depth of sediment to remove was determined by evaluating sediment phosphorus concentration data from USGS (2003). Based on the available USGS data, the total phosphorus concentration (% dry weight) for sediment in the study impoundments was highest for sediment depths up to three feet, as illustrated in Figure 5-1. With increasing sediment depth in the impoundments, total phosphorus concentration was generally less than half of the total phosphorus concentration as compared to the upper most one to two feet of sediment. Therefore, the greatest impact of sediment removal would be achieved by removing (on average) three feet of sediment depth in the impoundments.

The representative sediment volumes removed and the linear extent of dredging in each impoundment in for the sediment removal scenario are summarized in Table 5-3.

Table 5-3. Extent of Dredging in Model Scenario.

Dam	Sediment Volume Removed (acre-ft)
Aluminum City	1,050
Allen Street	13,800
Hudson	39,100
Gleasondale	21,800
Ben Smith	212,200
Powdermill	31,000

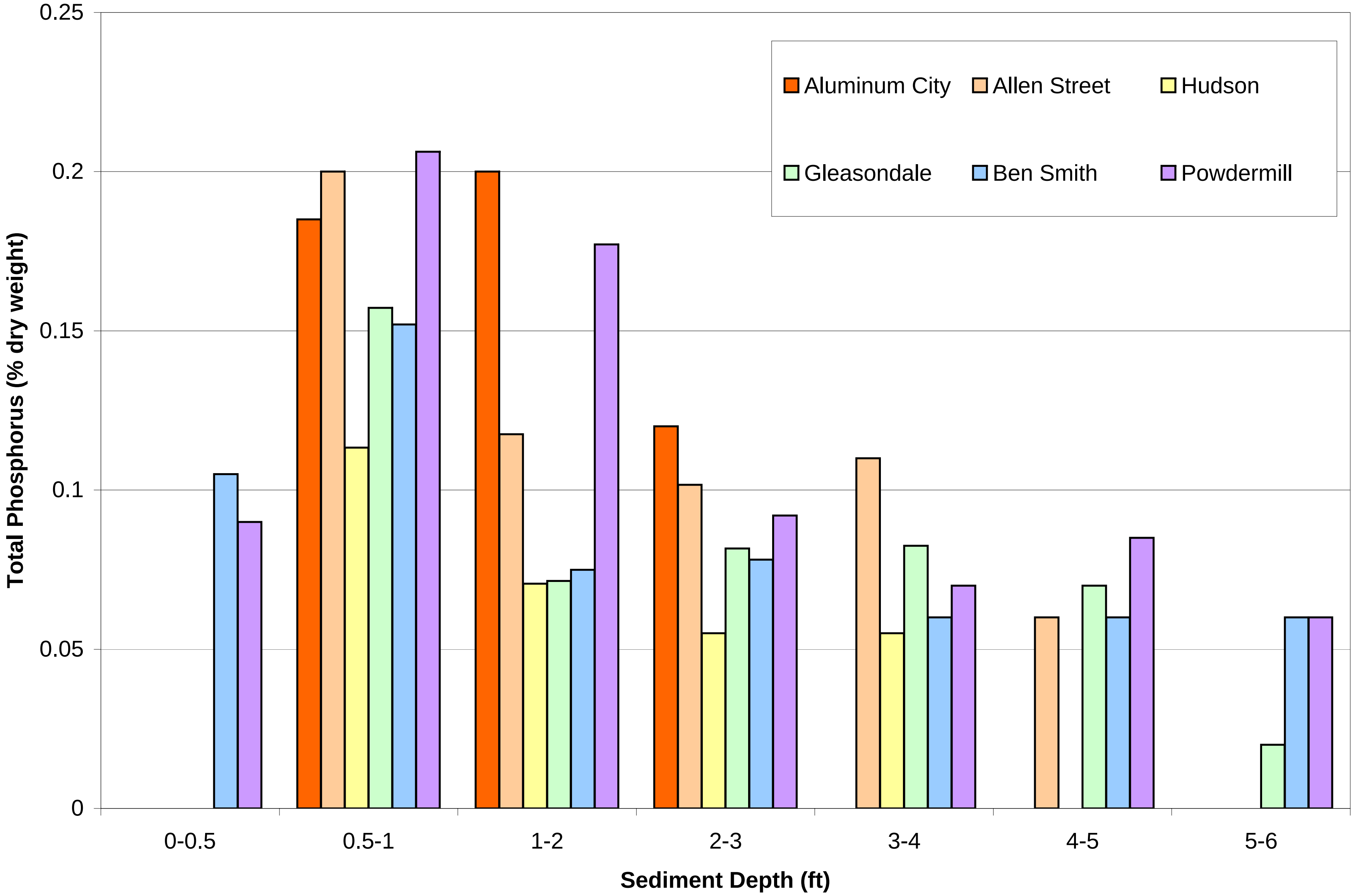


Figure 5-1
Sediment P Concentration vs. Depth
(USGS, 2003)

Sediment Transport

The effect of dredging/sediment removal on sediment transport is summarized in this section. The effect of dredging/sediment removal on sediment transport was evaluated by calculating the change in thalweg elevation for each study impoundment. It was anticipated that the thalweg elevation for each impoundment would decrease with dredging/sediment removal initially in the dredged area, and then return to pre-dredging conditions over a certain period of time. For this analysis, the affected river cross-sections were modified in the HEC-6 model to reflect a dredged impoundment. Then the HEC-6 model was run for a 20 year period, to assess the changes in thalweg elevation over the long term.

As expected, within a simulation period of five years, the dredged areas filled in from the settling of instream sediments. The change in bed profile due to dredging, both initially and after 20 years is depicted in Appendix E, Figure E-5. Currently, the river is stable and the sediment transport is balanced. On an annual basis, all sediment that enters the river discharges at the downstream end. During low flow conditions, some settling may occur, but this material is re-suspended during larger storm events. Dredging deepens the river and lowers river velocities and increases residence times in the impoundment. This leads to greater settling of sediment and the filling in of the dredged areas.

Water Surface Profiles

The effects of sediment removal on water surface profiles in the Assabet River are summarized here. In the HEC-RAS model, the river cross sections were modified to reflect dredging. Then the HEC-RAS model was used to simulate the range of flow conditions, including 7Q10, summer average, 10-year flood flow and 100-year flood flow.

Results of the simulations indicate that the water surface profiles do not change with dredging of the impoundments. The dam crest controls the water surface elevations and dredging of the impoundments has no effect. Additionally, the water surface does not change when the dredged areas fill-in with sediment.

Water Quality

The water quality of the Assabet River was simulated using the HSPF model. The HSPF model was modified to reflect the sediment removal in the impoundments using the hydraulic information from HEC-RAS to create new F-tables for HSPF. Additionally, the P flux model was used to determine the phosphorus sediment flux as a result of dredging/sediment removal in the impoundments.

The findings of the water quality simulations are as follows:

- Reduced sediment phosphorus flux lasts only for a few years. As the dredged area fills-in, the phosphorus flux increases back to levels similar to planned improvements.
- Dredging reduces residence time in impoundments which reduces reaeration and dissolved oxygen and increases algal growth.

Overall, dredging of the impoundments does not improve water quality. The hydraulic changes from the deeper impoundments more than offset the benefit from reduced sediment phosphorus flux. Also, within 5 years, the dredged areas refill to existing bed conditions. The sediment phosphorus flux reduction in the impoundments is initially estimated to be 80 percent due to dredging, but this benefit will be lost after a short period of time. After the dredged areas fill back in, the phosphorus flux reduction is estimated to be 60 percent, which will be the result of the planned improvements at the WWTFs.

5.2.5 Remove Gleasondale, Hudson and Ben Smith Dams

This scenario examined the changes in sediment bed, water surface profile and water quality from the removal of Gleasondale, Hudson, and Ben Smith dams. This scenario represents restoring the majority of the lower portion of the river back fully to a free-flowing, riverine system. This scenario includes the planned improvements as discussed in Section 5.2.2.

Sediment Transport

The findings for sediment transport for removing the three dams are similar to that of removing all six dams. Removing a dam can allow movement downstream of the sediment behind the dam. Dam removal reduces river depth and increases flow velocity in the areas behind the removed dam. The finer sediment behind the dam may move downstream because of the new, higher river velocities. The HEC-6 model was used to determine if any sediment material moved after dam removal, and if sediment did move, how much sediment was transported downstream.

The river bed profiles for the Base Conditions and the bed profile after 20 years with the three dams removed are presented in Appendix E, Figure E-3. Sediment transport would occur if Hudson, Gleasondale and Ben Smith dams were removed, as depicted in the figure, and some amount of dredging (to be calculated as part of a future task of this study) will need to occur to minimize downstream sediment movement.

Water Surface Profiles

Cross-sectional information to represent the three dams in the HEC-RAS model was revised to reflect dam removal and various flow conditions simulated. The HEC-RAS model results indicate that dam removals will significantly lower the water surface elevations for the 7Q10, summer average flow, 10-year flood, and the 100-year flood flow conditions. Table 5-4 present the change in depth behind each of the dams for the four flow conditions. Water surface profiles for the three dam removal scenario are included in Appendix F, Figure F-3.

Table 5-4. Change in water surface elevation for various flows scenarios. (All values in feet).

Dam	7q10	Summer Average	10 year	100 year
Hudson	-7.0	-6.9	-5.4	-3.4
Gleasondale	-4.7	-4.5	-4.5	-5.0
Ben Smith	-7.5	-7.5	-5.6	-4.0

Water Quality

The water quality of the Assabet River was simulated using the HSPF model. The HSPF model was modified to reflect the three dam removals using the hydraulic information from HEC-RAS to create new F-tables for HSPF. Additionally, the P flux model was used to determine the phosphorus sediment flux as a result of removing the three dams.

The water quality significantly improved with the removal of the three dams. The sediment phosphorus flux is anticipated to be reduced by 80 percent starting at the Hudson impoundment and continuing to the Concord River with the removal of the three dams. The reduction in sediment phosphorus flux is due to several factors, including reduced algal and macrophyte growth and reduced residence time in the system. In addition to the reduction in sediment phosphorus flux, the shallower river depths resulting from dam removal also result in increased reaeration and dissolved oxygen in the system, contributing to overall water quality improvement.

5.2.6 Remove Ben Smith Dam

This scenario examined the changes in sediment bed, water surface profile and water quality from the removal of Ben Smith dam. This scenario includes the planned improvements discussed in Section 5.2.2.

Sediment Transport

The findings for removing Ben Smith dam are similar to other dam removal scenarios. The HEC-6 model was used to determine if any sediment material moved after dam removal, and if sediment did move, how much sediment was transported downstream. The river bed profile for the Base Conditions and the bed profile after 20 year with Ben Smith dam removed are included in Appendix E, Figure E-4. Sediment transport would occur if Ben Smith dam is removed, as depicted in the figure, and some amount of dredging (to be calculated as part of a future task of this study) will need to occur to minimize downstream sediment movement.

Water Surface Profiles

Cross-sectional information to represent Ben Smith dam in the HEC-RAS model was revised to reflect dam removal and various flow conditions simulated. The HEC-RAS model results indicate removing Ben Smith dam will significantly lower the water surface elevations for the 7Q10, summer average flow, 10-year flood, and the 100-year flood flow conditions. Table 5-5 present the change in depth behind Ben Smith dam for the four flow conditions. The water surface profile resulting from removal of Ben Smith dam is included in Appendix F, Figure F-4.

Table 5-5. Change in water surface elevation for various flows scenarios. (All values in feet).

Dam	7q10	Summer Average	10 year	100 year
Ben Smith	-7.4	-7.4	-5.6	-4.0

Water Quality

The water quality of the Assabet River was simulated using the HSPF model. The HSPF was modified to reflect the removal of Ben Smith dam using the hydraulic information from HEC-RAS to create new F-tables for HSPF. Additionally, the P flux model was used to determine the sediment phosphorus flux as a result of removing Ben Smith dam.

The water quality improved with the removal of Ben Smith dam. Due to removal of the Ben Smith dam, the sediment phosphorus flux is anticipated to be reduced by 70 percent, beginning at the Ben Smith dam impoundment and continuing to the Concord River, including the Powdermill impoundment.

The reduction in sediment phosphorus flux is due to several factors, including reduced algal and macrophyte growth and reduced residence time in the system. In addition to the reduction in sediment phosphorus flux, the shallower river depths resulting from removing Ben Smith dam also result in increased reaeration and dissolved oxygen in the system, contributing to overall water quality improvement.

Section 6
Summary and Conclusions

This section includes a summary of study findings and discusses study conclusions.

6.1 Planned Improvements

Results of this study suggest that significant strides will be made toward the TMDL goal of 90% reduction in sediment phosphorus flux and overall improved water quality when the current planned improvements are in place at the WWTFs. Improvements are anticipated to be fully operational by 2010. The study indicated that planned improvements and the goal of 90% reduction of sediment phosphorus flux are *not* independent, and that the planned WWTF improvements are likely to collectively yield a significant reduction in sediment flux.

In addition to the planned improvements at the WWTFs, additional alternatives that would further contribute to meeting TMDL goals are summarized in the following sections.

6.2 Sediment Removal/Dredging

Sediment removal/dredging in the impoundments does not achieve study objectives and is not a viable alternative for meeting the TMDL goal of 90% reduction in sediment phosphorus flux. Sediment removal/dredging also does not contribute to the Assabet River meeting Massachusetts State Water Quality Standards for dissolved oxygen, acceptable levels of biomass production, and acceptable ambient phosphorus concentrations.

Results of this study indicate that in the long term, sediment removal/dredging has a detrimental affect on water quality in the six study impoundments. Dredging would deepen impoundments, resulting in increased residence time, and reduced dissolved oxygen and re-aeration in the impoundments Short-term benefits of dredging include an initial reduction in sediment phosphorus flux, with an approximate duration of less than two years, after which the sediment flux would likely return to current levels. However, this estimated initial reduction in phosphorus flux is overshadowed by the detrimental affects of dredging on long term water quality in each impoundment.

Furthermore, due to the dynamic nature of the Assabet River system, dredging is an undesirable alternative because it does not contribute to source reduction of the phosphorus into the system. Minimizing the phosphorus load from nonpoint and point sources, as well as limiting biomass growth in the impoundments, are the key factors in sediment phosphorus flux reduction and overall water quality improvement in the Assabet River. That is, the flux of phosphorus from the sediments is more dependent on recent loadings from upstream than on long-term historical deposition and accumulation. Dredging would primarily address long-term deposition (which was determined *not* to be the driving factor in this river), and would not effectively alter the short-term dynamics of upstream loads, biological productivity, settling, and re-introduction into the water column via diffusive flux.

6.3 Dam Removal

Dam removal, coupled with localized sediment removal immediately upstream of each dam, would achieve study objectives and contribute significantly to meeting the TMDL goal of 90% reduction in sediment phosphorus flux. Dam removal will contribute to the Assabet River meeting Massachusetts State Water Quality Standards for dissolved oxygen, acceptable levels of biomass production, and acceptable ambient phosphorus concentrations.

Dredging sediment behind each dam would be associated with any dam removal alternative, for the purposes of preventing downstream movement of sediment once the dam is removed. Estimated quantities of sediment to remove with each dam are being calculated as part of ongoing study tasks.

Results of this study indicate that in the long term, dam removal, particularly Ben Smith Dam and Hudson and Gleasondale Dams to a lesser extent, would provide significant water quality benefits. Dam removal reduces residence time in the impoundments, which has the cascading effect of the following additional benefits:

- Improves reaeration in impoundments
- Improves dissolved oxygen
- Decreases biomass growth
- Reduces sediment phosphorus flux

The removal of Ben Smith dam is a key component contributing to the system meeting the TMDL goal of 90% sediment phosphorus flux reduction, since the biomass growth and settling that ultimately drives the sediment flux would decrease. The removal of Hudson and Gleasondale dams would contribute incrementally to this goal. Coupled together, the removal of all three dams would result in a decrease in impounded volume of the Assabet River of 415 acre-feet.

Removal of the two most upstream dams, Aluminum City and Allen Street, would contribute to the reduction in sediment phosphorus flux and overall water quality improvement for the impoundment associated with each dam. However, the nature of the sediment phosphorus flux reduction and other water quality improvements would be localized. Results of the modeling suggest removal of these two dams is not as high a priority for meeting the TMDL goal for sediment phosphorus flux reduction as is the removal of Hudson, Gleasondale and Ben Smith Dams.

Similar to conclusions drawn regarding Aluminum City and Allen Street dam removals, the removal of Powdermill dam would also contribute to the reduction in sediment phosphorus flux and overall water quality improvement for the Powdermill impoundment. Removal of the Powdermill dam would have a more significant improvement to water quality compared to removal of the Aluminum City and Allen Street dams. However, the nature of the sediment phosphorus flux reduction and other water quality improvements would again be quite localized. Results of this study suggest removal of Powdermill dam is not as a high priority for meeting the TMDL goal as is the removal of Hudson, Gleasondale and Ben Smith dams. However, the removal of the Powdermill dam would have a more significant improvement to water quality compared to removal of the Aluminum City and Allen Street dams.

Removing Ben Smith dam, located immediately upstream of the Powdermill impoundment, perhaps is the most significant factor in improving water quality and reducing sediment phosphorus flux in the Powdermill impoundment. Due the large size of the Ben Smith impoundment, and the long residence time, the Ben Smith impoundment is a significant contributor of biomass growth affecting both the Ben Smith and Powdermill impoundments. Due to the large size of the impoundment, if Ben Smith dam were to stay in place, significant biomass growth would continue to occur, resulting in existing levels of sediment phosphorus flux in both the entire length of the Ben Smith impoundment, and continuing downstream to the Powdermill impoundment, and beyond.

6.4 Summary of Water Quality Findings

A summary of the water quality conditions (both current and predicted) due to planned improvements, dredging and dam removal is captured in Table 6-1 below. A full discussion of the water quality changes expected from the alternatives is included in Section 5 of this report. The set of models were applied for each alternative. The expected water quality changes are presented in a subjective (non-numeric) method, because the updated HSPF model is not calibrated for the new hydraulic representation. Each alternative was simulated using the revised HSPF model, but rather than indicate the exact numeric results, only the change from the Base Condition is presented.

The Base Condition scenario indicates water quality problems with dissolved oxygen, high biomass from high levels of phosphorus. The most significant of the water quality problems occur in the larger impoundments, Hudson, Gleasondale, Ben Smith, and Powdermill.

The Planned Improvements scenario include a reduction of phosphorus to 0.1 mg/l in the discharge during the summer and 1.0 mg/l during the winter months for the WWTFs. The planned improvements produce several beneficial changes in water quality. First, the lower phosphorus in the WWTF produces lower instream concentrations of phosphorus. The lower phosphorus concentration in the river limits the biomass growth and improves dissolved oxygen. Additionally, the lower biomass in the river produces less biomass to settle to the sediment, which in turn reduces phosphorus flux from the sediment back to the overlying water. This alternative reduces the instream phosphorus and the recycling of phosphorus through the sediments. The expected improvements in water quality from the Base Conditions will be substantial, but it is not expected to achieve the full 90 percent reduction needed in sediment phosphorus flux to meet the TMDL goal.

Sediment removal/dredging with the goal of reducing the phosphorus flux will not improve water quality in the river system. This alternative was simulated the HSPF model which predicted a negative impact on water quality. Though the phosphorus sediment flux will be reduced, the benefit will only last a few years (estimated 2 to 5 years). The phosphorus sediment flux is “driven” by the biomass growth and instream phosphorus concentrations. Additionally, up to 3 feet of sediment will need to be dredged to effectively reduce the phosphorus sediment flux based on past sediment cores by USGS. This sediment dredging increases the impoundment volumes which has several negative impacts on water quality. With the sediment removal/dredging alternative, the residence time would be longer in each impoundment, which would allow additional biomass growth, which in turn will increase sediment phosphorus flux. Also, reaeration (transfer of oxygen from the air to the water) would be reduced in each impoundment from the deeper impoundment depths.

Removing all 6 dams would have a very beneficial impact on water quality. The set of models were simulated to determine the changes in hydraulics and water quality from removing the dams. Removing a dam would have multiple benefits in water quality. First, the residence time in each impoundment would be reduced which would reduce the biomass growth in the river.

Removing the dams for the larger impoundments would have the largest benefits. Removing Ben Smith dam would have the largest benefit; Hudson, Gleasondale, and Powdermill dam removals would have the next best benefits, and Aluminum City and Allen Street would have the smallest benefits. A second benefit from removing dams would be reduced sediment phosphorus flux from the reduced biomass growth. Less biomass growth would produce less algae to settle and less phosphorus cycling through the sediments. The sediment phosphorus flux reduction is expected to be approximately 80 percent, near the TMDL target of 90 percent reduction, if three of the larger dams (Hudson, Gleasondale and Ben Smith) were removed. A third benefit from dam removal is increased reaeration in the shallower water depths. Increased reaeration will improve dissolved oxygen in the river.

Table 6-1. Summary of Water Quality Findings, Various Alternatives

Dam	Base Condition (2000)	Planned Improvements	Dredging	Dam Removal
Aluminum City	🟢	🟢	–	+
Allen Street	🟢	🟢	–	+
Hudson	🟡	🟢	–	++
Gleasondale	🟡	🟢	–	++
Ben Smith	🔴	🟡	–	+++
Powdermill	🟡	🟢	–	++
Downstream Load to Concord River	🟡	🟢	–	+

Legend

Existing Conditions: 🟢 = Good, 🟡 = Fair, 🔴 = Poor

Improvements: (–) = No improvement, (+) = some improvement,
(++) = good improvement, (+++) = significant improvement

A summary of the anticipated P flux reductions for various alternatives is shown in Table 6-2 below. These findings are based on results from the HSPF model and the P flux model.

Table 6-2. Summary of Anticipated P Flux Reduction, Various Alternatives

Scenario	**P-Flux (mg P/m2-day)**	**P Flux Change**	**Sediment P(3) Load (lbs/day)**
Base Condition	D/S(1): 21.6 U/S(1): 12.0	No Change	28.0 (4)
Planned Improvements (WWTP TP @ 0.1 mg/l summer 1.0 mg/l winter	D/S: 8.6 U/S: 4.8	60% reduction	11.2
Dam Removal – 6 dams(2)	D/S: 4.3 U/S: 2.4	80%	4.2
Dam Removal – 3 dams (Hudson, Gleasondale, Ben Smith) (2)	D/S: 4.3 U/S: 4.8	80% (Hudson and d/s only) 60% (u/s – same as planned improvements)	6.7
Dam Removal – 1 dam(2) (Ben Smith only)	Ben Smith and d/s: 6.5 Gleasondale and u/s: 4.8	70% (Ben Smith and d/s only) Gleasondale and u/s same as planned improvements	8.4
Dredging – short term(2)	D/S: 4.3 U/S: 2.4	80%	5.6
Dredging – long term(2)	D/S: 8.6 U/S: 4.8	60% (planned improvements)	11.2

Notes:

1) U/S notates impoundments D/S notates Gleasondale and downstream .
2) Includes Planned Improvements
3) Sediment P Load includes reduction in P flux and reduction in sediment bed area associated with dam removal.
4) From the Assabet River TMDL Study, September 2005, page 42. The TMDL set a goal of 90% reduction from 28.0 lbs/day of Total P to a value of 2.8 lbs/day of Total P.

6.5 Additional Considerations

During the TMDL study, and even during the outset of this study, the sediment phosphorus flux process was not well understood for the river. This study helped gain an understanding of the dynamic nature of sediment phosphorus flux in the Assabet River. Further efforts should be undertaken to better understand the nature of the sediment-water interface, and the influence of sediment phosphorus flux rates on instream water quality.

Both the sediment phosphorus flux field data collected, as well as the mass balance model of sediment flux, led to better understanding of the seasonality associated with sediment phosphorus flux. Results of the study indicate that the sediment response to a change in overlying water phosphorus concentration is fairly short (several seasons). This suggests that incremental improvements in either point or nonpoint sources should yield benefits in the river in a time frame of several years, rather than a longer period of time as initially hypothesized.

This realization suggests that an adaptive approach would be advantageous. That is, the planned improvements at the WWTFs could be instituted and their impacts measured within a few years to see how extensive further improvements may need to be. This can be concurrent to the feasibility studies for dam removal. Study findings suggest further efforts should focus on the influence of nonpoint sources in this watershed, and the potential associated improvements in sediment phosphorus flux and water quality associated with nonpoint source reductions.

This study also resulted in significant findings regarding the seasonality of sediment phosphorus flux. An additional consideration to meet the TMDL target of 90% reduction in sediment phosphorus flux is winter phosphorus discharge limits for at WWTFs. Based on results of this modeling effort, it was concluded that winter limits for the WWTFs, below the current planned limit of 1 mg/l would contribute significantly to the reduction in sediment phosphorus flux.

If no other improvements were implemented, further reductions in summer P discharge limits, below 0.1 mg/L, would not contribute significantly to further reduction in sediment phosphorus flux. This is because the winter instream phosphorus concentration has such a strong effect on the P flux the following summer. Therefore, if the summer P discharge limits were decreased below 0.1 mg/L without any further reduction in winter limits, the P flux in the summer would still be "controlled" by the winter instream phosphorus concentration.

6.6 Summary of Study Findings

Results of this modeling study suggest that the most beneficial improvements to Assabet River water quality can be achieved through planned WWTF improvements, dam removal, and consideration of lower winter effluent limits than currently planned. More specifically, the following is a summary of study findings:

- Expect reduction of 60% of sediment phosphorus flux from planned WWTF improvements (Phosphorus discharge limit of 0.1 mg/l summer and 1.0 mg/l winter).
- Remove Ben Smith dam and if possible, Gleasondale and Hudson/Rt 85 dams. Remove sediment behind dams as part of dam removal to prevent sediment from moving downstream subsequent to dam removal.
- Lower winter WWTP Phosphorus discharge below 1.0 mg/l
- Dredging or sediment removal is not an effective alternative in reducing sediment flux. Dredging/sediment removal is only proposed in conjunction with dam removal to prevent the redistribution of accumulated sediment.
- Nonpoint source reductions, including Phase II stormwater management and enhanced golf course management, should be considered.
- An adaptive strategy would be advantageous, since the response of the river to the alternatives evaluated in this study is anticipated to occur within a few years. The planned WWTF improvements should proceed, and impacts should be measured concurrently with the process of planning and design for dam removal. It may also be beneficial to test the impacts of lower winter effluent phosphorus limits in the near term, since this study suggests this winter limits significantly impact sediment phosphorus flux rates in the following growing seasons.

Section 7
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