CDM

Upper Merrimack and Pemigewasset River Study

Model Plan

Prepared for:

New Hampshire Department of Environmental Services

New England District – U.S. Army Corps of Engineers

December 2007

The State of New Hampshire
DEPARTMENT OF ENVIRONMENTAL SERVICES

Thomas S. Burack, Commissioner

Mr. Kirk Westphal, P.E.
Camp Dresser and McKee
50 Hampshire St.
Cambridge, MA 02139

Subject: Upper Merrimack and Pemigewasett River Study Model Plan

Dear Mr. Westphal,

Thank you for preparing the "Upper Merrimack and Pemigewasett River Study Model Plan". We believe that this plan in conjunction with the "Upper Merrimack and Pemigewasett River Study Field Sampling Plan" will enable us to successfully achieve our goal of creating a time-dependent model of flow and water quality that can be used to guide water resource decisions for both wastewater and water supply now and in the future.

As New Hampshire's population in the Merrimack River basin continues to grow, inevitable consequences of such growth occur. These include higher discharges and potentially higher pollutant loadings to the Merrimack and Pemigewasett Rivers, from wastewater treatment facilities and increased pressure on public water suppliers to withdraw more water from the same rivers to help satisfy the increasing demand for potable water These two public uses are inter-related and, if not managed properly, can adversely impact water quality and/or quantity as the intensity of use increases.

Development of a model is necessary to accurately simulate the many complex aquatic interactions that impact water quality and to efficiently and accurately evaluate the myriad of existing and future wastewater discharge, impoundment management, and water supply withdrawal scenarios for the purpose of identifying the most feasible combinations that will be protective of water quality standards.
Specifically, we, and many stakeholders along the rivers, look forward to using this model to answer important water management questions such as the following:

- What is the predicted impact of existing water supply withdrawals on river flow?
- What is the predicted water quality in the Merrimack and Pemigewasett Rivers under existing water supply withdrawals and existing and permitted wastewater discharge loadings for oxygen demanding pollutants?
- If water quality standard violations are predicted under existing permitted conditions, where do they occur and what would the wastewater treatment effluent limits have to be to attain water quality standards?
- How do existing dam operations impact water quantity and quality and how would these conditions change if the dams were operated differently?
- What is predicted impact of future water supply withdrawals on river flow?

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- What would the wastewater effluent limits for oxygen demanding pollutants have to be to attain water quality standards under future wastewater flows and future water supply withdrawal and dam operation scenarios?
- What combinations of effluent limits, nonpoint source best management practices and impoundment management are needed to restore existing dissolved oxygen impairments?
- What opportunities are there for coordinated impoundment management among state, federal, and private dam owners to better achieve flood control and aquatic life support, while meeting the needs of wastewater dischargers?

These important questions, all involving scenario-playing for future conditions, cannot be sufficiently quantified for public discussion by observation and monitoring of existing conditions alone. A model is needed.

Thank you once again to you and your staff for preparing this excellent report and we look forward to working with you on the development of this model.

Sincerely,

Paul M. Currier, P.E., P.G.
Administrator, Watershed Management Bureau
NH Department of Environmental Services

cc: Barabara Blumeris, ACOE
Gregg Comstock, NHDES
Peg Foss, NHDES

Table of Contents

Table of Figures

List of Tables

1 Introduction

1.1 Study Overview

The Merrimack River is formed by the confluence of the Pemigewasset and Winnipesauke Rivers at Franklin, NH and discharges to the Atlantic Ocean near Newburyport, MA. The Merrimack River has a total drainage area of 5,010 square miles with three quarters of the watershed in New Hampshire and one quarter in Massachusetts.

Within the past several decades, significant improvements have been made to the water quality of the Merrimack River. However, water quality, quantity, and fish and wildlife habitat and migratory corridor concerns remain. Recently, CDM assisted the United States Army Corps of Engineers (USACE) and project sponsors in Massachusetts and New Hampshire in completing modeling and analyses on the Lower Merrimack River as part of the Merrimack River Watershed Assessment (MRWA) (CDM, 2006a; CDM, 2006b). The goal of this work was to compare the relative contributions and impacts of pollution from nonpoint sources and combined sewer overflows, and also to compare alternative bacteria abatement strategies in the watershed.

The Upper Merrimack and Pemigewasset River (UMPR) Study will build upon and extend the data base, modeling, analyses, and lessons learned from the MRWA. Extensive field monitoring is planned throughout the Upper Merrimack Watershed to augment the database of water quality measurements compiled as part of the MRWA. Additionally, the computer models developed for the MRWA will be extended northward to encompass the Upper Merrimack Watershed, so that they can be used to guide water resource decisions in New Hampshire, including:

- Total Maximum Daily Load allocations for oxygen demanding substances
- Water supply withdrawals from the mainstem, and the associated impacts on flow and water quality
- Potential for alternative management of dams and impoundments throughout the watershed, particularly USACE dams.

Portions of the Merrimack River and Pemigewasset Rivers are listed on the NH 2006 303(d) list of impaired waters for dissolved oxygen violations. Dissolved oxygen levels in portions of the upper river fall below standards required to support aquatic life. Part of this study is to identify sources of pollutants and the impacts that various management and regulatory decisions may have on the attainment of dissolved oxygen water quality standards to support aquatic life in the river.

Several wastewater treatment facilities (WWTFs) are at or near their design capacity and will soon need to expand. However, before design of the upgraded plants can begin, new WWTF discharge permit limits are needed to ensure attainment of water quality standards for dissolved oxygen.

The tools developed for this assessment may be used to help establish effluent limits for all WWTFs in the study area, which, in turn, will allow communities to expand to accommodate future growth and be protective of surface water quality and the aquatic habitat in the receiving waters. The assessment will consider factors that can contribute to oxygen depletion such as carbonaceous oxygen demand (CBOD), ammonia (NH3) and total phosphorus (TP), among others.

1.2 Study Area Definition

The study area includes portions of the Merrimack River Watershed that drain to the mainstem of the Merrimack River in New Hampshire. Part of this area includes the Nashua River basin, most of which is in Massachusetts but drains into the Merrimack River in New Hampshire. The sections of the mainstem in Massachusetts, and the watersheds draining to these sections, will not be included in this study. Earlier modeling for the MRWA focused on the river downstream of Hooksett Dam, just north of Manchester, with low-resolution hydrologic and loading simulation of drainage areas further upstream. Modeling for this study will incorporate the watershed with more detailed modeling in the river reaches and impoundments from Lincoln to Manchester including, as appropriate, the Winnipesauke watershed. A map of the study area is provided in Figure 1-1.

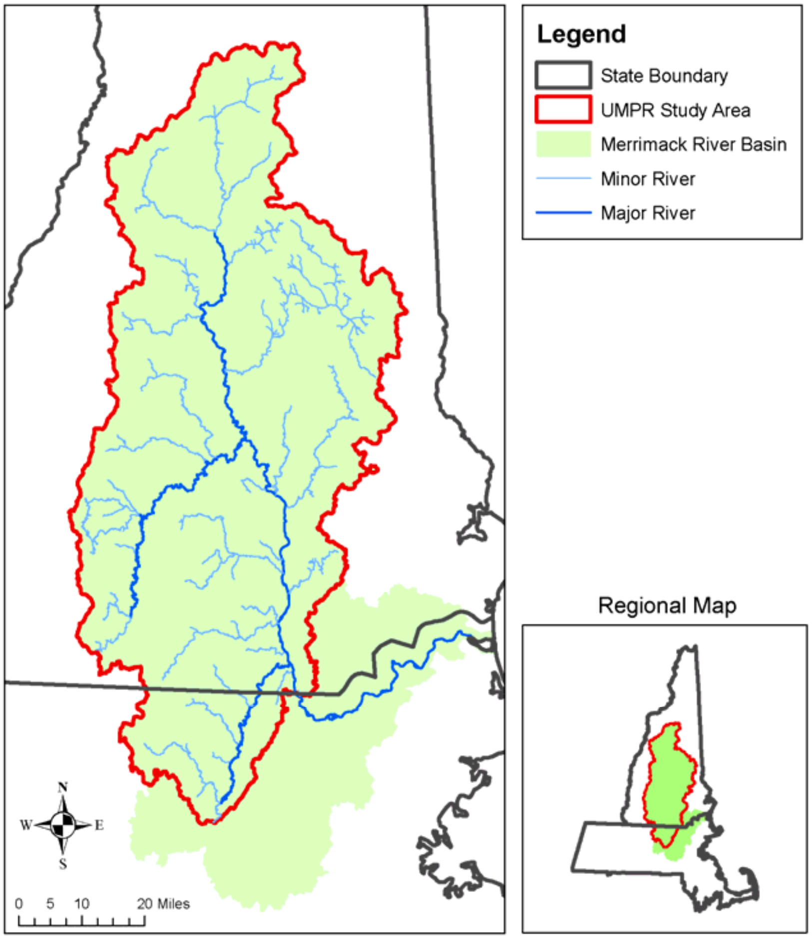


Figure 1-1: Study area

1.3 Modeling Objectives and Approach

This section discusses the modeling objectives and approach which will be used in the Upper Merrimack and Pemigewasset River Study. The approach provides a broad overview of the modeling strategy with detailed discussion of each individual model provided in subsequent sections.

1.3.1 Modeling Objectives

The modeling objectives of this study are to

- Represent pollutant sources and in-stream processes affecting dissolved oxygen and chlorophyll a (phytoplankton, periphyton, and macrophytes, as necessary) levels in the mainstem of the Upper Merrimack and Pemigewasset Rivers.
- Evaluate controls on pollutant sources to achieve attainment of water quality standards.

1.3.2 Conceptual Model

Before developing and implementing the detailed computer simulation models discussed below, a conceptual model will be created in order to identify and evaluate all potential factors and processes that may impact the levels of dissolved oxygen and chlorophyll in the river. This simple model will be useful for improving our overall understanding of the water quality dynamics in the river and for guiding decisions that may arise during development of the simulation models.

1.3.3 Dilution Calculations

An initial assessment of total phosphorous (TP) loads will be performed using simple dilution calculations to help guide subsequent monitoring and modeling efforts on the Upper Merrimack and Pemigewasset Rivers. Since it is generally the limiting nutrient in rivers, excess phosphorous is expected to be a main driver of dissolved oxygen impairments, which are the focus of this study. The relative impacts of various TP loads (e.g. from point and nonpoint sources) on the instream concentrations are currently unknown and will be better understood through this assessment.

Background concentrations will be estimated from previous monitoring and modeling efforts. Volumetric dilution calculations for existing and prospective effluent concentration ranges will then be used to estimate instream TP concentrations under various conditions, including low-flow (7Q10) conditions. These concentrations will be compared to water quality guidelines for TP to identify any locations along the river that may be receiving relatively large loads. This analysis will provide important insights into the overall TP mass balance of the river and may help identify locations where higher resolution may be warranted in either the monitoring or modeling programs.

1.3.4 Simulation Models

The simulation models developed for this study will be based on the existing models from the MRWA study used to conduct water quality assessments on the Lower Merrimack River (CDM, 2006a). The structure of the overall model will be similar to the existing MRWA model, but will require some modifications. The three major components of the model will include

- Nonpoint Source Hydrologic and Water Quality Modeling using HSPF
- River Hydraulics Modeling using SWMM
- In-Stream Water Quality Modeling using WASP

The SWMM hydraulic routing model will act as an intermediary between HSPF, which will model overland flow and non-point source pollutants, and WASP, which will model water quality through the hydraulic simulation provided by SWMM. Accurate water quality simulation in WASP will be dependent on the accuracy of the hydraulic information generated by the SWMM model (travel times, depths, velocities, etc.).

The existing model also includes five combined sewer overflow (CSO) models for simulating urban runoff and pollutant loading from urban areas draining to combined sewer systems. These models were included in the MRWA model to simulate CSO discharges, which were a primary concern addressed by the MRWA study. Since the focus of the UMPR study is on dissolved oxygen and chlorophyll a (i.e. nutrients), instead of bacteria levels, the existing CSO models may be removed and replaced by urban runoff simulation in the nonpoint source component of the HSPF model. This would greatly simplify the modeling suite, with potentially little detrimental impact in the ability of the tools to evaluate dissolved oxygen dynamics. A flow diagram of the modeling scheme excluding the CSO models is provided in Figure 1-2. If the CSO models are not removed, the modeling scheme will be identical to that described in the MRWA Modeling Report.

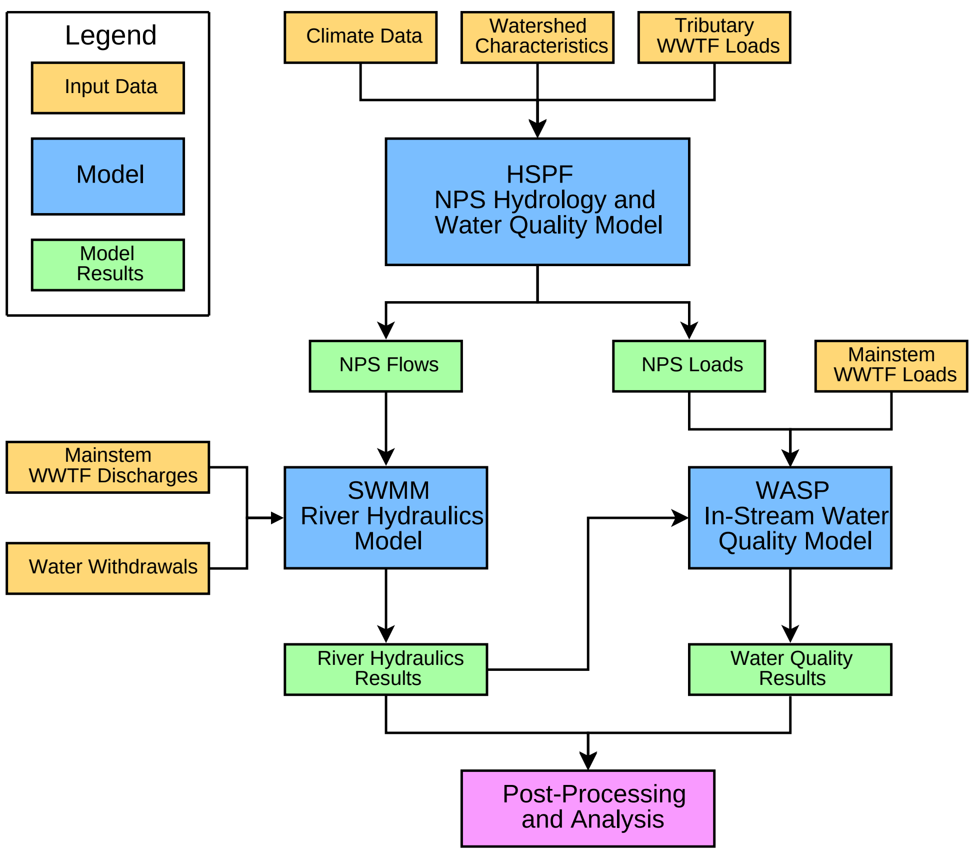


Figure 1-2: Overall Model Schematic without CSO Models

Generally, the modeling philosophy, tools, and approach will be very similar to those employed for the MRWA. However, in addition to the possible removal of the CSO models from the model structure, four other modifications to the existing models will be necessary:

- Extending all three models into the Upper Merrimack River Watershed, which involves re-discretizing the northern basins in the HSPF model and extending the river channel in SWMM and WASP.

- Potentially extending the timeframe of simulations to include the winter season (although there may be other alternatives).

- Accounting for possible impoundment stratification in the river hydraulics and in-stream water quality models.

- Including sediment oxygen demand and nutrient fluxes to the water column in the in-stream water quality model.

1.4 Calibration Philosophy

The models that will be used for this study are complex, and some general guidelines for defensibly calibrating the models must be established. The following guidelines are identical to those applied to the original MRWA models. The procedures, parameters, and performance measures that were used to calibrate the hydrologic and water quality components of the original MRWA HSPF model are provided in Appendix A. More specific descriptions of calibration methods for each model developed for this study are included in subsequent sections, but the following general premises will be applied:

- The watershed and in-stream water quality models (HSPF and WASP) have many parameters that can influence simulated responses within the model. As such, there are thousands of combinations of parameter values that would reproduce observed physical phenomena. To help ensure that the models reproduce physical cause-and-effect relationships, and to avoid asserting good performance based solely on mathematical goodness-of-fit statistics, the following guidelines will be followed:

  - Parameters that can be fixed as constants (based on observed or literature values) will be identified, and held constant during the calibration process.

  - The number of tuning parameters (values that are varied during the calibration process) will be minimized; only parameters which have the greatest influence on model output will be varied.

- Spatial variability in parameters (without justification) will be avoided – Global values, or values that can be directly linked to physical features of the landscape or river, will be used to the greatest extent possible.

- Accurate hydraulic routing is a necessary precursor to simulation of in-stream processes. The in-stream water quality model will be calibrated once it is demonstrated that the hydraulic model simulates accurate travel times.

- The modeling system is a cascade of information. Each model will be calibrated independently to observed data, but the ultimate measure of usefulness will be the in-stream water quality model. Adjustments will be made to the HSPF model based on observations of the WASP simulations.

2 Watershed Modeling

2.1 Introduction

Hydrologic Simulation Program – FORTRAN (HSPF) Version 12 will be used to simulate non-point source runoff flows and loads to the main-stem of the Upper Merrimack and Pemigewasset Rivers. Unlike the SWMM and WASP components of the MRWA model, the existing HSPF model includes the entire Merrimack River watershed, not just the sections south of Manchester. However, to achieve the objectives of the UMPR study, representation of the Upper Merrimack River basin in HSPF will be improved through greater spatial resolution and supporting field data. The hydrologic output generated by the HSPF model will be used as input in the SWMM hydraulic routing model, and will include watershed runoff and tributary discharges to the mainstem of the river; the water quality output from HSPF will be used as input in the WASP in-stream water quality model to represent point and non-point source pollutant loads to the mainstem of river.

2.2 Overview of HSPF

HSPF simulates runoff flows and pollutant loads from watershed point and non-point sources to receiving waterbodies. The main component of HSPF is a hydrologic model that calculates surface runoff, interflow, and baseflow from pervious and impervious areas in the watershed and routes these flows through successive river reaches and reservoirs.

A typical HSPF application divides a large watershed into multiple sub-watersheds, each having its own set of distinct characteristics. Because HSPF is a lumped parameter model, the characteristics and parameters of each sub-watershed are assumed to be uniform.

Flows and pollutant loads from the different land uses in the sub-watersheds are routed to an in-stream river model. Point-source flow and pollutant loads such as from treatment plants or industrial discharges can be incorporated directly into the model.

HSPF is a continuous simulation model meaning it can perform simulations over a long time period, as opposed to over discrete storm events. A great deal of input data is required to set up and calibrate the model. These include watershed characteristics, climate data, and observed streamflow and water quality. The model is capable of detailed output of the hydrologic and water quality conditions on pervious and impervious land surfaces, in the soil profile, and in water bodies.

In summary, HSPF allows the user to simulate both point source and non-point source runoff and pollutant loads from a watershed to a receiving waterbody. This watershed view facilitates a comprehensive assessment of pollutant sources, fate, and transport required for Total Maximum Daily Load (TMDL) computations, or for analyzing management alternatives.

2.3 Model Development

The existing HSPF model developed for the MRWA study will be used as a basis to model non-point source runoff and loads for the UMPR study. Although a significant amount of effort will be saved by using the existing model, some important modifications will be necessary to achieve the objectives of this study.

2.3.1 Watershed Delineation

In the existing HSPF model, the Merrimack River Watershed is divided into multiple sub-watersheds, each of which is assumed to have uniform (lumped parameter) hydrologic and water quality properties within its own boundaries. Since the focus of the MRWA study was on the lower section of the Merrimack River, less spatial resolution was needed in the Upper portion of the Merrimack River Watershed, which was sub-divided into watersheds of considerably larger areas. In order to extend the existing model to the Upper Merrimack and Pemigewasset Rivers (and to match the resolution of forthcoming field data with the spatial resolution of the model), the northern river basin will be re-delineated into sub-watersheds with smaller areas.

The delineation of the new sub-watersheds will be based on existing sub-watershed delineations from the USGS Hydrologic Unit Code (HUC) classification system. HUC classifications are part of a nation-wide system intended to facilitate the analysis and modeling of surface water features and watersheds. The location of USGS streamflow gages will also be considered since it is useful for calibration purposes to have gages located at the most downstream point of a sub-watershed.

Based on these two factors, CDM proposes using the sub-watershed delineation shown in Figure 2-1. Included in this figure are the locations of active streamflow gages, some which will be used for calibration, as well as the original HSPF sub-basin delineation used in the MRWA study. To minimize changes to the existing model, only the sub-watersheds north of Manchester will be re-delineated.

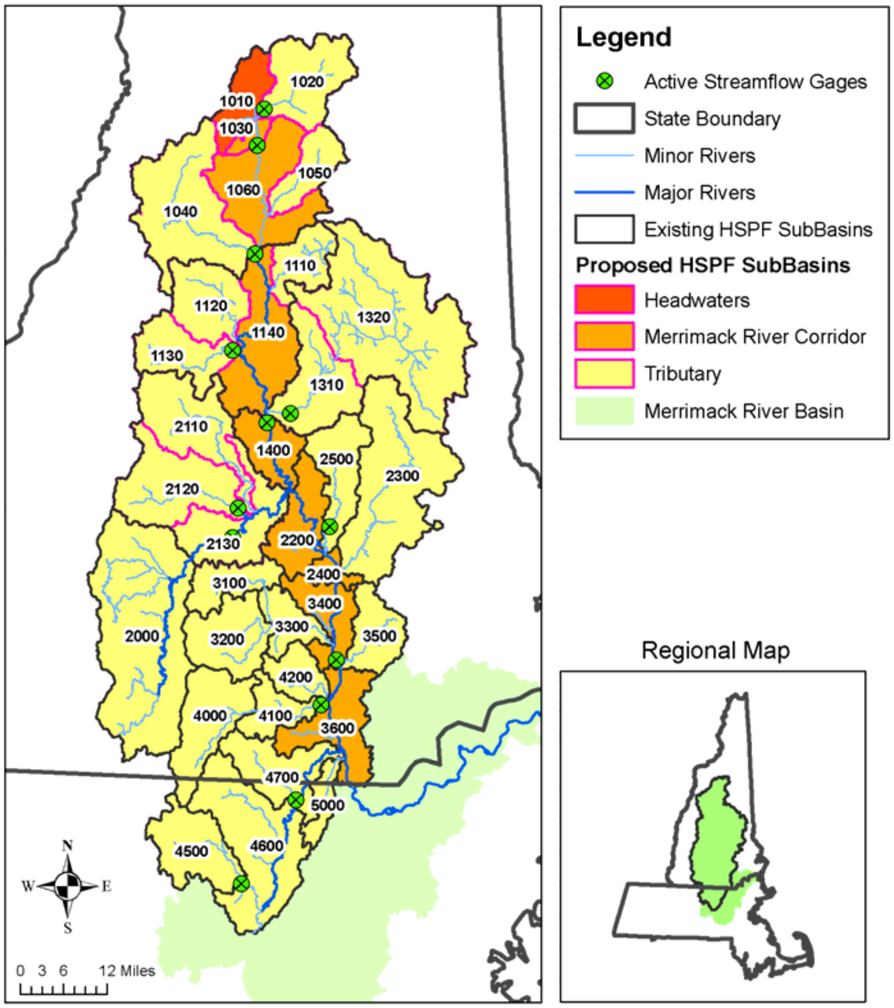


Figure 2-1: Proposed sub-watershed delineation for HSPF

Each proposed sub-basin was assigned a 4-digit code based on the 3-digit codes from the existing HSPF sub-basin delineation. For basins that were not re-delineated, a zero was appended to the right of the original 3-digit codes. For example, the sub-basin having the code 320 from the original model will be assigned the code 3200. Each sub-basin that was re-delineated retained the first two digits of the original code followed by a unique third digit followed by a zero. For example one proposed sub-basin from the original basin 110 will be assigned the code 1110. The code and names for each proposed sub-watershed in the Upper Watershed are listed in Table 2-1.

Table 2-1: Proposed sub-basin delineations for HSPF

Code	Sub-Basin Name	Area (mi^2)
1010	Headwaters	63.0
1020	East Branch Pemigewasset River	116.7
1030	Merrimack Corridor 1	15.5
1040	Baker River	213.4
1050	Mad River	62.2
1060	Merrimack Corridor 2	151.6
1110	Squam River	65.2
1120	Newfound River	98.7
1130	Smith River	87.8
1140	Merrimack Corridor 3	148.5
1310	Winnipesaukee River	123.3
1320	Lake Winnipesaukee	362.5
1400	Merrimack Corridor 4	66.8
2000	Upper Contoocook River	366.7
2110	Blackwater River	135.0
2120	Warner River	148.5
2130	Lower Contoocook River	113.8
2200	Merrimack Corridor 5	89.7
2300	Suncook River	255.9
2400	Merrimack Corridor 6	22.1
2500	Soucook River	91.4
3100	Upper Piscataquog River	61.9
3200	South Branch Piscataquog River	103.9
3300	Lower Piscataquog River	51.8
3400	Merrimack Corridor 7	73.6
3500	Cohas Brook	69.9
3600	Merrimack Corridor 8	108.8
4000	Upper Souhegan River	117.3
4100	Lower Souhegan River	53.2
4200	Baboosic Brook	49.1
4500	Upper Nashua River	103.5
4600	Middle Nashua River	212.0
4700	Lower Nashua River	100.6
5000	Salmon Brook	30.7

The four original HSPF sub-watersheds that will be re-delineated into smaller units are listed in Table 2-2.

Table 2-2: Proposed re-delineations of the Upper Merrimack Watershed.

Original Basin	Proposed Sub-Basin	% Original Basin Area
100 – Pemigewasset, Upper	1010 - Headwaters	10%
100 – Pemigewasset, Upper	1020 - East Branch Pemigewasset River	19%
100 – Pemigewasset, Upper	1030 - Merrimack River Corridor	2%
100 – Pemigewasset, Upper	1040 - Baker River	34%
100 – Pemigewasset, Upper	1050 - Mad River	10%
100 – Pemigewasset, Upper	1060 - Merrimack River Corridor	24%
110 – Pemigewasset, Lower	1110 - Squam River	16%
110 – Pemigewasset, Lower	1120 - Newfound River	25%
110 – Pemigewasset, Lower	1130 - Smith River	22%
110 – Pemigewasset, Lower	1140 - Merrimack River Corridor	37%
130 – Winnipesaukee River	1310 - Winnipesaukee River	25%
130 – Winnipesaukee River	1320 - Lake Winnipesaukee	75%
210 – Contoocook, Lower	2110 - Blackwater River	34%
210 – Contoocook, Lower	2120 - Warner River	37%
210 – Contoocook, Lower	2130 - Lower Contoocook River	29%

2.3.2 CSO Models

With the focus of the original MRWA on bacteria level exceedences in the mainstem of the river, runoff from areas that drain to combined sewer systems were simulated using five CSO models that were developed prior to and independently of the MRWA model. The areas accounted for by the CSO models were clipped from the sub-watershed delineations used in HSPF in order to avoid double-counting the runoff and loads from these areas.

Since the focus of this study is on dissolved oxygen depletion under low flow conditions, detailed simulations of CSO discharges, which occur only under high flow conditions, may no longer be necessary and removal of the CSO models will be considered. Removal of these models would simplify the overall river model and allow for greater flexibility in the range of scenarios being investigated.

If removal of the CSO models is justified, the sub-watersheds that had originally been clipped to exclude CSO drainage areas will be returned to their original boundaries. The HSPF model would then simulate drainage from the entire Merrimack River Watershed including areas draining to combined sewer systems. Removal of the CSO models would affect the five sub-basins listed in Table 2-3. It may be necessary to increase BOD loads from the areas with combined sewage during severe rain events to account for the potential oxygen-depleting discharge, although the durations of discharge would necessarily be very short.

Table 2-3: Sub-basins affected by removal of CSO models.

Code	Name	CSO Municipality
3300	Lower Piscataquog River	Manchester, NH
3400	Merrimack Corridor 7	Manchester, NH
3600	Merrimack Corridor 8	Nashua, NH
4700	Lower Nashua River	Nashua, NH
5000	Salmon Brook	Nashua, NH

2.3.3 Simulation Under Winter Conditions

One of the modeling objectives of this study is to simulate water quality conditions of the Upper Merrimack and Pemigewasset Rivers year-round in order to provide support for the development of cold weather WWTF permit limits. Since physical, chemical and biological processes in the river vary seasonally, cold weather permit limits for ammonia, carbonaceous oxygen demand (CBOD5), and phosphorous can be significantly different than warm weather limits. The existing Lower Merrimack River model simulates only non-winter conditions between May 1 and October 31 since the focus of the previous study was on elevated bacteria levels which are more prevalent during the warmer seasons.

In order to simulate non-point source runoff during winter months, significant modifications and additions to the HSPF model would be required since hydrologic processes during winter are inherently more complex than during warmer seasons (ground freezing, precipitation freezing, etc.). To incorporate these processes, a number of additional parameters would be required to account for snow accumulation, snow melt, and freezing temperatures, among others, which would significantly increase the complexity of the model. CDM believes that the amount of effort required to make these modifications would far exceed the resulting benefits and that one of two alternatives to winter simulation may be more feasible and effective.

Alternative Winter Simulation Method

CDM proposes using actual USGS streamflow measurements (transposed in ungaged basins) instead of HSPF simulations to represent watershed runoff during winter months. Pollutant loads from point and non-point sources during winter months will be calculated by multiplying the measured streamflows by average inflow concentrations of the water quality constituents. Average concentrations of the pollutants will be based on values found in the literature and through online water quality databases such as the EPA STORET database. For sub-watersheds that are not monitored by USGS gages, winter streamflows will be estimated using regressions of simulated streamflows and pollutant loads with similar gaged sub-watersheds.

Revert to 6-month Simulation Only

If it is confirmed that observed DO violations occur primarily in summer months and during low flow, it may not be necessary to include full-year simulation. However, if it is found that sediment affects (SOD and nutrient flux) contribute significantly to oxygen demand in the river, offline long-term analysis (outside of the models) may be warranted to account for long-term accumulation and depletion of nutrients and oxygen-demanding substances in the sediments.

2.3.4 Watershed Characteristics

Once the sub-watersheds have been re-delineated, the model parameters representing the properties of these watersheds will be re-calculated. Watershed parameters include

- Drainage Area
- Land Use
- Infiltration Capacity
- Interception Storage
- Other Hydrologic Parameters

2.3.5 River/Reservoir Reach Characteristics

HSPF simulates streamflow using a hydrologic routing algorithm based on simple relationships between depth, volume, and flow. For the original model, more effort was focused on estimating these properties for the tributaries that discharge into the lower portion of the Merrimack River. For the UMPR model, the hydraulic properties of the tributaries in the Upper Merrimack Watershed will be re-evaluated more accurately using similar methods as those used in the original study.

2.3.6 Climate Data

The existing climate datasets will be updated to include the most recent available data at the same meteorological stations used for the existing models. .

2.4 Model Calibration and Validation

The parameters, performance measures, and procedures used to calibrate the HSPF model will be based on those used for the original HSPF model, which are provided in Appendix A.

The hydrologic component of the original HSPF model was calibrated using observed daily streamflow measurements collected by USGS streamflow gages at 13 locations on the Merrimack River and its tributaries. Although only gaged basins were used for the hydrologic calibration, the resulting parameters were transferred from gaged to ungaged basins based on the assumption of hydrologic similarity. Ungaged basins adjacent to or downstream of a gaged basin shared the same hydrologic parameters. This method will again be utilized to calibrate the characteristics of ungaged basins for the present study. The MWRA calibration plan for the existing HSPF model is included in Appendix A of this document.

For this study, the hydrologic parameters in HSPF will be calibrated using 13 long-term, active streamflow gages shown in Figure 2-2 and listed in Table 2-4.

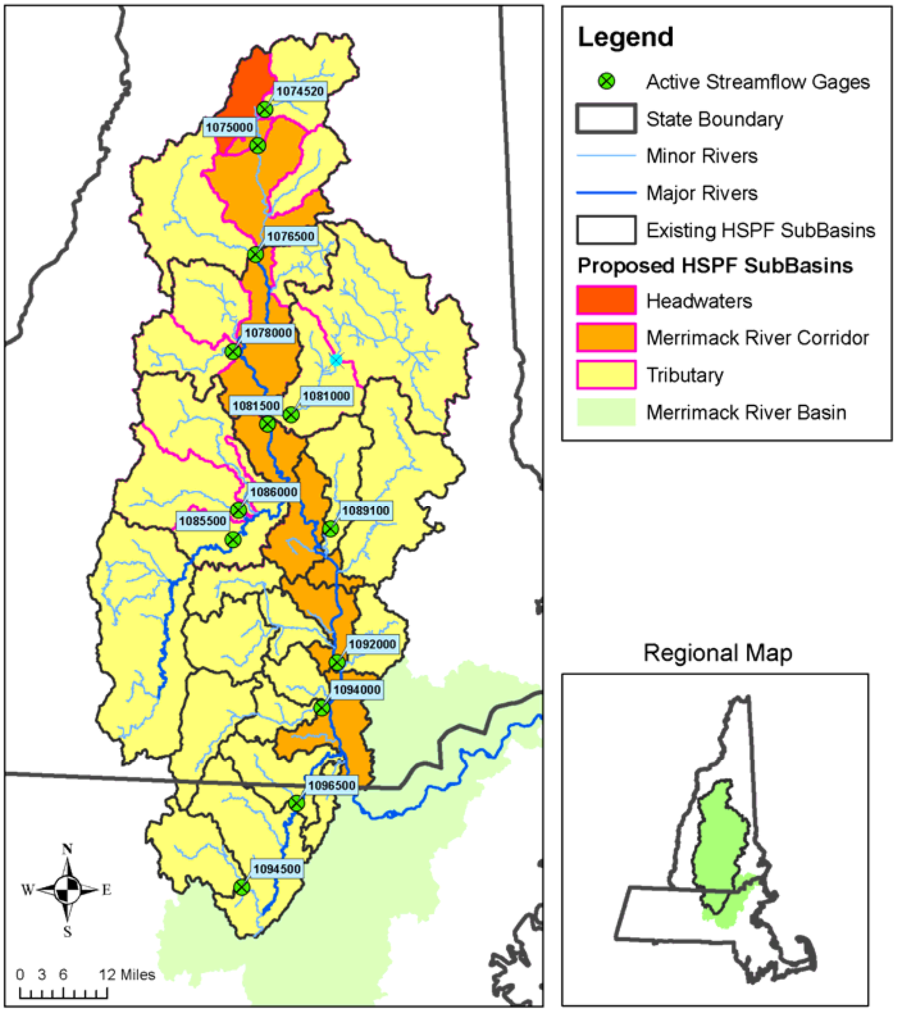


Figure 2-2: Proposed USGS Streamflow Gages for HSPF Calibration

Table 2-4: Proposed USGS Streamflow Gages for HSPF Calibration

Gage ID	Station Name	Latitude	Longitude	Drainage Area (mi²)	Record Begins
01074520	East Branch Pemigewasset River at Lincoln, NH	44°02"51'	71°39"37'	115.0	03/10/93
01075000	Pemigewasset River at Woodstock, NH	43°58"34'	71°40"48'	193.0	10/01/39
01076500	Pemigewasset River at Plymouth, NH	43°45"33'	71°41"10'	622.0	10/01/03
01078000	Smith River near Bristol, NH	43°33"59'	71°44"54'	85.8	05/11/18
01081000	Winnipesaukee River at Tilton, NH	43°26"30'	71°35"17'	471.0	01/01/37
01081500	Merrimack River at Franklin Junction, NH	43°25"22'	71°39"12'	1,507.0	08/01/03
01085500	Contoocook River below Hopkinton Dam at Hopkinton, NH	43°11"34'	71°44"52'	427.0	08/06/63
01086000	Warner River at Davisville, NH	43°15"03'	71°43"58'	146.0	10/01/39
01089100	Soucook River at Pembroke Road near Concord, NH	43°12"49'	71°28"51'	81.9	03/01/88
01092000	Merrimack River near Goffs Falls, Manchester, NH	42°56"53'	71°27"50'	3,092.0	11/21/36
01094000	Souhegan River at Merrimack, NH	42°51"27'	71°30"24'	171.0	07/13/09
01094500	North Nashua River near Leominster, MA	42°30"06'	71°43"23'	110.0	09/17/35
01096500	Nashua River at East Pepperell, MA	42°40"03'	71°34"32'	435.0	10/01/35

Validation of the HSPF model will be performed by comparing model results to observed streamflow measurements for periods of time not used for calibration. In addition to this validation procedure, other validation checks will be employed for surface water flows under low-flow conditions and for groundwater dynamics.

The NH DES and the USGS have developed an analytical tool for estimating streamflows from ungaged basins based on regression equations between streamflow and basin characteristics. This tool will be used to further validate the predictions of the HSPF model for ungaged basins.

The accuracy of groundwater simulations produced by the HSPF model may also be compared to results from a regional groundwater model for the Lower Merrimack basin in New Hampshire being developed by the USGS (pending availability of output for corresponding time periods, and the ability to easily convert groundwater elevations from the groundwater model to aquifer storage volumes in the HSPF model). The HSPF representation of groundwater is more conceptual than the USGS groundwater model representation, and model-to-model correspondence may be difficult to verify. However, the regional USGS model will be evaluated, as it may be useful for validating the groundwater dynamics predicted by the HSPF model.

3 Hydraulic Modeling

3.1 Introduction

The USEPA's Stormwater Management Model (SWMM), version 4.4h, will be used to create a hydraulic routing model of the mainstem Upper Merrimack and Pemigewasset River from Lincoln, NH to Manchester, NH.

3.2 Overview of SWMM

The EXTRAN (Extended Transport) block of SWMM 4.4h is capable of performing fully dynamic hydraulic routing of flows in open and closed conduits of any complexity, such as branching systems, tidally-influenced systems, regulated systems, and systems with dynamic backwater effects. While SWMM has the capabilities through its RUNOFF block to perform hydrologic modeling, it will not be used for such tasks in this study. Rather, the SWMM hydraulic routing model will act as an intermediary between HSPF, which will model overland flow and non-point source pollutants, and WASP, which will model water quality through the hydraulic simulation provided by SWMM. The flows and loads associated with point source discharges and water withdrawals along the mainstem of the river will not be generated by any of the three models, and instead will be represented by information obtained during the Field Sampling Program.

3.3 Model Development

The existing model of the Merrimack River, which covers the river from the Hooksett Dam in Hooksett, NH to Newburyport, MA where it discharges to the Atlantic Ocean, will be extended to include the study area of the Upper Merrimack and Pemigewasset River Study. The existing model is represented in SWMM with 139 links—each covering approximately 0.5 mile sections of the mainstem—that are connected at nodes. Links permit flow from node to node; nodes are storage elements in the system. All inflows, such as tributary flows from HSPF or point source discharges, are input at the nodes. Continuity is maintained at the nodes; continuity and momentum are conserved in the links. Extension of the model will include segmenting the upstream portion of the Merrimack River and the Pemigewasset River and gathering necessary data for input to the SWMM hydraulic model. Table 3-1 provides a summary of the data required to develop the SWMM model of the Upper Merrimack River system.

Table 3-1: SWMM Data Requirements

Nodes	Channel
Ground surface elevation	Channel type
Invert elevation	Length
Surface area	Cross-section geometry
Boundary conditions	Manning's n value
	Upstream vertical offset
	Downstream vertical offset

3.3.1 Channel Characteristics

The base of the hydraulic model is the river's physical geometry and channel characteristics. This section describes how the 115-mile segment of the Upper Merrimack and Pemigewasset mainstem will be represented in SWMM. The study area also includes several water withdrawals from the mainstem and point source discharges, and six major dams that must be included in the hydraulic model.

Mainstem Geometry

In order to create the hydraulic and water quality model for the Lower Merrimack River, the 80-mile mainstem channel was represented in SWMM by a series of 139 conduits. The conduits were each approximately 0.5 to one-mile in length depending on the geographic location and the complexity of the mainstem channel (i.e. bends, constrictions, etc). The river was segmented based on available transect data from two sources: field bathymetric surveys collected as part of the MRWA, and Federal Emergency Management Agency (FEMA) Flood Insurance Study back-up data available for several communities along the mainstem Merrimack River.

The same methodology will be applied to the Upper Merrimack and Pemigewasset River in order to discretize the 115-mile mainstem channel. The Lower Merrimack SWMM model extends into the current study area from the Massachusetts-New Hampshire state line to the Hooksett Dam in Hooksett, NH; therefore further segmentation of that 30-mile reach is unnecessary. Approximately 55 miles of the 85-mile stretch that is included in the study area, but not covered by the Lower Merrimack model, is covered by FEMA Flood Insurance Study back-up data. Transects are available from FEMA for 15 communities along the mainstem from Hooksett, NH upstream through Woodstock, NH. The additional 30 miles of the Upper Merrimack and Pemigewasset Rivers have been segmented based on channel complexity (i.e. bends, constrictions, etc). Prior to model development, transects will be surveyed, as needed, to complete the segmentation of the mainstem and confirm the accuracy of FEMA transects.

Figure 3-1 shows the available and proposed mainstem channel segmentation of the study area. Additional, more detailed, maps of the channel segmentation are included in Appendix B.

Dam and Impoundment Geometry
Transects will be surveyed at locations within the impounded reaches as indicated in Figure 3-1. Section 3.3.5 contains more detailed information about the proposed representation of the six study area dams.

Roughness Coefficient
SWMM uses Manning's n roughness coefficients to perform hydraulic routing through the river segments. Initial estimates for channel bed roughness will be taken from the FEMA Flood Insurance Study back-up data in the form of HEC-RAS input files. Adjustments will be made to these values, and reaches not covered by FEMA will be characterized, based on a future hydraulic survey of the study area.

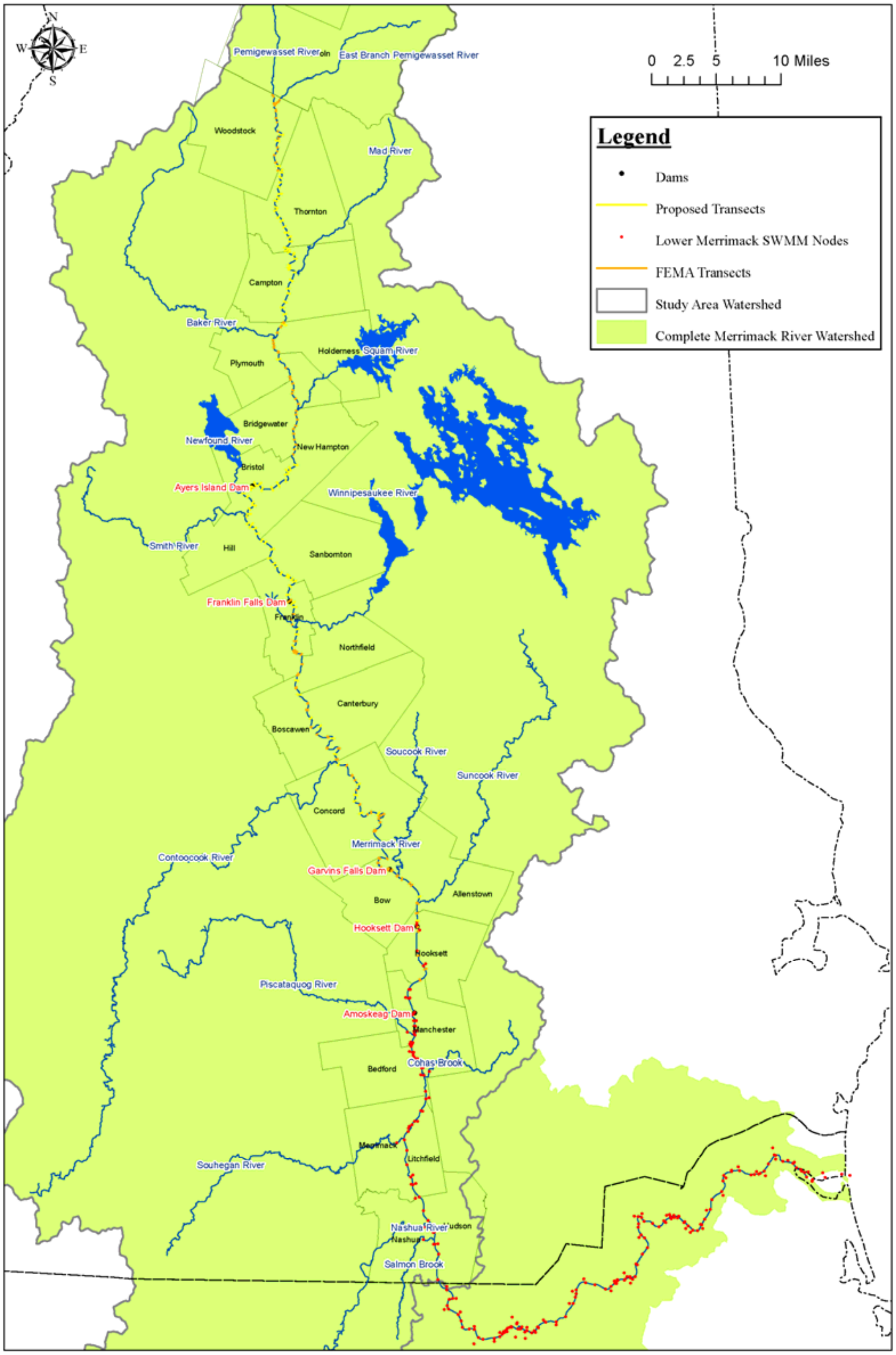


Figure 3-1: SWMM Channel Segmentation and Transects

3.3.2 Boundary Conditions

In the existing Lower Merrimack River SWMM model, developed as part of the Merrimack River Watershed Assessment Study, the Hooksett Dam acts as the upstream boundary condition and the Atlantic Ocean tides act as the downstream boundary condition. This model is to be extended during the Upper Merrimack and Pemigewasset River Study, preserving the model structure downstream of the current study area. Therefore, the downstream boundary condition will continue to be the Atlantic Ocean tides, using data from the National Oceanic and Atmospheric Administration's (NOAA's) Center for Operational Oceanographic Products and Service records for the Portland, Casco Bay, Maine tide station. This will provide dynamic boundary conditions and backwater effects up to the state line and avoid the need to estimate an artificial boundary condition there. The extended model will be run through the downstream reach to the ocean, but it will not be re-calibrated or used for output downstream of the current study area.

In the extended model, the most upstream SWMM node will receive flow from the HSPF sub-basin (#1010) that represents the headwaters of the Pemigewasset River. This node will act as the upstream flow boundary condition for the SWMM hydraulic model.

3.3.3 Withdrawals

Water withdrawals from the mainstem Upper Merrimack and Pemigewasset River will be modeled in the SWMM hydraulic model using in-line lift pumps (type 2). They will be configured to match the actual operating rules of the withdrawal points that they represent—typically constant pumping with a shut-off rule if the river depth reaches a specified low point. The pumps will be located at the SWMM nodes that are nearest to the actual location of the withdrawal point. Table 3-2 lists the name and location of the water withdrawals along the mainstem Merrimack and Pemigewasset Rivers. Not all of the following water users will be included in the model; a revised list will be developed based on usage data.

Table 3-2: Surface Water Withdrawals on the Mainstem

Town	Water User	
Bedford, NH	Manchester Country Club	
Hudson, NH	Green Meadow Golf Club Brox Industries, Inc.	Coastal Concrete Company
Litchfield, NH	Wilson Farm of NH Passaconaway Country Club Continental Paving Inc.	Pennichuck Water Works Lockheed Martin Corp.
Londonderry, NH	Pennichuck Water Works Century Village Comm Assn. Moose Hill Orchards Inc.	Londonderry Country Club Continental Paving, Inc.
Manchester, NH	Public Service Co. NH Intervale Country Club Nylon Corp of America Manchester Water Works	Saint Anselm College Coastal Material Corporation F&S Transit Mix Co.
Merrimack, NH	Pennichuck Water Works Merrimack Village District Anheuser-Busch Inc.	Jones Chemicals Inc. Lockheed Sanders Texas Instruments Inc.
Nashua, NH	Nashua Country Club Pennichuck Water Works Brox Industries Inc. Redimix Concrete Service Inc. Nashua National Fish Hatchery Unifirst Corporation Advanced Circuit Tech. Beebe Rubber Company Coca-Cola USA Compaq Computer Corp. GL&V Impco-Jones Inc. Hampshire Chemical Corp	Kollsman Lockheed Sanders Nashua Corporation Owens-Brockway Sanmina Corporation Teradyne Connect Systems Rivier College Saint Joseph Hospital Southern NH Medical Center Sky Meadow Country Club Mine Falls Ltd Partnership Nashua Hydro Associates

3.3.4 Tributaries and Point Source Discharges

Tributary and Hydrologic Corridor Discharges

HSPF will be used to generate and route flows from the hydrologic corridors and mouths of major tributaries to the mainstem of the Upper Merrimack and Pemigewasset River. Hydrologic corridors are defined as areas outside of the major tributary basins that discharge directly to the mainstem. These flows are loaded into SWMM at the appropriate node location; in some cases more than one source may enter the same conduit.

Point Source Discharges

Point source discharges, including WWTF and industrial discharges, will be entered into the SWMM model at the respective SWMM nodes. Model input flows will be based on daily discharge data from the respective facility. Table 3-3 lists the name, type and location of the point source dischargers along the mainstem Merrimack and Pemigewasset Rivers. The industrial dischargers list will be revised based on discharge data.

Table 3-3: Point Source Discharges to the Upper Merrimack and Pemigewasset River

Facility Name	Receiving Waters	Location
Municipal WWTFs		
Lincoln	Pemigewasset River-East Branch	Lincoln, NH
Woodstock	Pemigewasset River	North Woodstock, NH
Plymouth Village WWTF	Pemigewasset River	Plymouth, NH
Bristol WWTF	Pemigewasset River	Bristol, NH
Winnipesaukee River Basin	Merrimack River	Franklin, NH
Merrimack County Nursing Home	Merrimack River	Merrimack County, NH
Concord-Penacook	Merrimack River	Penacook, NH
Concord- Hall Street	Merrimack River	Concord, NH
Suncook	Merrimack River	Allenstown, NH
Hooksett	Merrimack River	Hooksett, NH
Manchester	Merrimack River & Piscataquog River	Manchester, NH
Derry WWTF	Merrimack River	Derry, NH
Merrimack	Merrimack River	Merrimack, NH
Nashua	Merrimack River & Nashua River	Nashua, NH
Industrial Discharges		
Bridgewater Power Company	Pemigewasset River	Ashland, NH
Public Service of New Hampshire	Merrimack River	Bow, NH
Nylon Corp. of America	Merrimack River	Manchester, NH
Anheuser-Busch Inc.	Merrimack River	Merrimack, NH
Jones Chemicals Inc.	Merrimack River	Merrimack, NH
Nashua Corporation	Merrimack River	Merrimack, NH
Hampshire Chemical Corp.	Merrimack River	Nashua, NH
Brox Industries Inc.	Merrimack River	Nashua, NH
Nashua National Fish Hatchery	Merrimack River	Nashua, NH
Lockheed Sanders	Merrimack River	Nashua, NH
Sanmina Corporation	Merrimack River	Nashua, NH

Source: USEPA PCS (http://www.epa.gov/enviro/html/pcs/) or Robin Neas (personal communication)

Two communities in Southern New Hampshire along the mainstem Merrimack River have combined sewer overflow (CSO) systems that were modeled separately from the mainstem SWMM model in the MRWA study. The Manchester CSO model (using SWMM) and the Nashua CSO model (using MOUSE) were loaded into the mainstem SWMM model at the appropriate node location. Given that the UMPR study is primarily focused on low-flow conditions in the river, the external CSO models may not be included in the current study. They are time-intensive to run alongside the other three mainstem models (HSPF, SWMM and WASP) and may not have significant impacts on the overall evaluation of nutrients and DO. If the CSO models are excluded from this study, the corresponding WWTFs in Manchester and Nashua will be treated as normal point source discharges, and the runoff from those urban areas will be modeled directly in HSPF then loaded into the appropriate SWMM nodes as tributary or hydrologic corridor flows.

3.3.5 Dam Operations

Representation in SWMM

Each of the six dams in the study area (Amoskeag Dam, Hooksett Dam, Garvins Falls Dam, Eastman Falls Dam, Franklin Falls Dam, and Ayers Island Dam) is unique and will be modeled differently in SWMM. Depending on the specific dam operations, decisions will be made about how to represent each on an individual basis. In general, the turbines of the hydroelectric dams will be represented by pumps, or a combination of weirs and orifices, as they were in the Lower Merrimack River model. This will allow for dam operations to be conditioned based on minimum and maximum flow requirements, depth, and fluctuations in flow. It is anticipated that the spillways will be represented as transverse horizontal weirs with characteristics matching those of the actual dam spillway. Canals will be represented as parallel conduits in SWMM, with the appropriate amount of water being routed through depending on actual dam operations.

Impoundment Stratification

After the completion of the Field Sampling Program under Task Order 2 of the Upper Merrimack and Pemigewasset River Study, the issue of stratification within the five impoundments along the mainstem will be better understood. For the purposes of this Modeling Plan, several different scenarios have been identified as potential methods for representing the effects of vertical stratification on the impoundments in the SWMM hydraulic model:

1) If the results of the Field Sampling Program indicate that a particular impoundment is stratified.

    a) If the withdrawal point from the impoundment is within the epilimnion.

       Under these conditions, the impoundment hydraulics will be represented in SWMM by separating the upper epilimnion layer and the lower hypolimnion layer and treating them as unique, parallel conduits. Each would have its own inflow and outflow specification (zero flow through the hypolimnion), and would be paired with a unique WASP segment as well. This would allow for the layers to have different temperatures and flow characteristics based on the actual impoundment stratification. When the withdrawal point is within the upper layer, the lower layer can simply be represented as an off-line pond in the model. Since the depth of the impoundment's thermocline varies extensively from one season to the next, different versions of the impoundment representation in SWMM may need to be developed to correspond with these seasonal changes, since the geometry of the representative channel cannot change dynamically during a model run.

b) If the withdrawal point from the impoundment is within the hypolimnion

This scenario is similar to the scenario described above, but in this case, both layers would receive inflow and discharge outflow. The stratified layers would be represented by two unique, parallel conduits in SWMM. However, when the water is being drawn from the hypolimnion, the respective conduit must have appropriate outflow characteristics to effectively represent the water quality and hydrodynamics of the stratified impoundment. Water would be drawn from the epilimnion to the hypolimnion in an equal amount to the discharge flow from the hypolimnion, maintaining a constant hypolimnion volume. Outflow from the epilimnion would be determined with the dynamic hydraulic equations in SWMM.

For both of the aforementioned scenarios, the parallel conduits representing stratified layers of an impoundment would correspond to unique segments in WASP, which is capable of two-dimensional modeling to simulate the dispersion of water quality constituents between layers and the downstream effect of impoundment stratification. While not an ideal plan, the possibility exists for the use of a separate modeling package that has better capabilities in overall reservoir hydrodynamic simulation. This approach would provide a more detailed representation of the impoundments; however that level of detail is not likely necessary at this stage of the study, since the existing models can be effectively manipulated to simulate both water and pollution flow through both layers of a stratified reservoir. The objective of this modeling effort is to effectively simulate the behavior of the Upper Merrimack and Pemigewasset River as whole, in order to highlight the possible causes of dissolved oxygen deficits and identify further plans to rectify the problem.

2) If the results of the Field Sampling Program indicate that the impoundment is not stratified.

If the impoundment is not stratified, the same modeling methodology will be applied that was used in the Lower Merrimack River model. The impoundment segments will be surveyed and represented in the model as riverine segments composed of series of conduits and nodes. In order to represent the dam, in-line control structures (weirs, orifice or pumps) will be placed at the location corresponding to the dam spillway and outflow works. Most likely, a combination of outflow structures and pumps will be used to effectively model the dam's operation.

3.4 Model Calibration and Validation

Unlike highly parameterized models, the only simulation parameter in this SWMM model that can significantly affect the routing of water in the open channel is the channel roughness. Other input data, such as channel cross section geometry, channel slope, etc. will be based on measured field data, and as such, will not be subject to calibration adjustment (assuming the slope and transect geometries are fixed, and are linearly interpolated between measured points). .

Based on the results of sensitivity runs on the existing model for the Lower Merrimack River, small changes in assumed roughness had little effect on travel time and water elevation throughout the river. Initial tests on the new model's sensitivity to roughness coefficients will be done to confirm this general response. It may be that in the faster-flowing and steeper reaches in the northern basin, the hydraulics are more sensitive to assumed roughness.

The performance of the SWMM model will be verified by evaluating the following hydraulic responses:

- Travel time over long reaches (from earlier USGS studies, and potentially from future task orders associated with this study)
- Water surface elevation (per USGS gage records)
- Impacts of dams on downstream hydrographs (as observed at mainstem USGS gages)

The hydraulic travel time in the simulation model will be evaluated by tracing synthetic conservative particles with WASP, using the flows generated by SWMM. Simulated results will be compared to dye studies to be completed under subsequent tasks of this study, and also to the results of a 2002 USGS travel times report that includes the Merrimack River (Smith, 2002). This method was successfully used to verify travel times in the SWMM model of the Lower Merrimack River.

The model's reproducibility of water surface elevation will be tested against measured data available for four USGS streamflow/stage gages along the mainstem Upper Merrimack and Pemigewasset Rivers. Two of those gages are a close (< 5 miles) distance downstream from study area dams and will be used to evaluate the simulated dam operation effects on modeled streamflow. Table 3-4 lists the four gages and their locations within the study area.

Table 3-4: USGS Streamflow Gages on the Mainstem

Gage Name	**Gage Number**	**Location**
Pemigewasset River at Woodstock	01075000	Upstream gage, near Pemigewasset headwaters
Pemigewasset River at Plymouth	01076500	Upstream of Ayers Island Dam, near Baker River confluence
Merrimack River at Franklin Junction	01081500	Just downstream of Franklin Falls Dam at the confluence of the Pemigewasset and Winnipesaukee Rivers
Merrimack River at Goffs Falls	01092000	Just downstream of Amoskeag Dam and Piscataquog River confluence

4 In-Stream Water Quality Modeling

4.1 Introduction

An in-stream water quality model of the mainstem Upper Merrimack and Pemigewasset River from Lincoln, NH to the Massachusetts-New Hampshire state line will be developed using the USEPA's Water Quality Analysis Simulation Program (WASP) Version 5.0.

4.2 Overview of WASP

The WASP model contains three sub-routines, two for water quality simulation- TOXI for the simulation of toxic pollutants, such as organic chemicals and metals, and EUTRO for the simulation of conventional pollutants, such as dissolved oxygen and nutrients- and one for hydrodynamic simulation (DYNHYD). For the purposes of the Upper Merrimack and Pemigewasset River Study, only the EUTRO kinetic subroutine will be used; hydrodynamic data will be fed to WASP from SWMM. A general description of the EUTRO subroutine is provided below; additional detail on the WASP model plan is provided in subsequent sections.

4.2.1 Water Quality Parameters

The EUTRO subroutine simulates the fate and transport of conventional pollutants in the water column; the following nine state variables may be modeled:

- Phytoplankton carbon
- Periphyton carbon
- Inorganic phosphorus
- Organic phosphorus
- Organic nitrogen
- Ammonia-N
- Nitrate
- Dissolved oxygen
- CBOD

Figure 4-1 provides a schematic of the EUTRO sub-routine reactions. Additional, parameter-specific discussion is provided below.

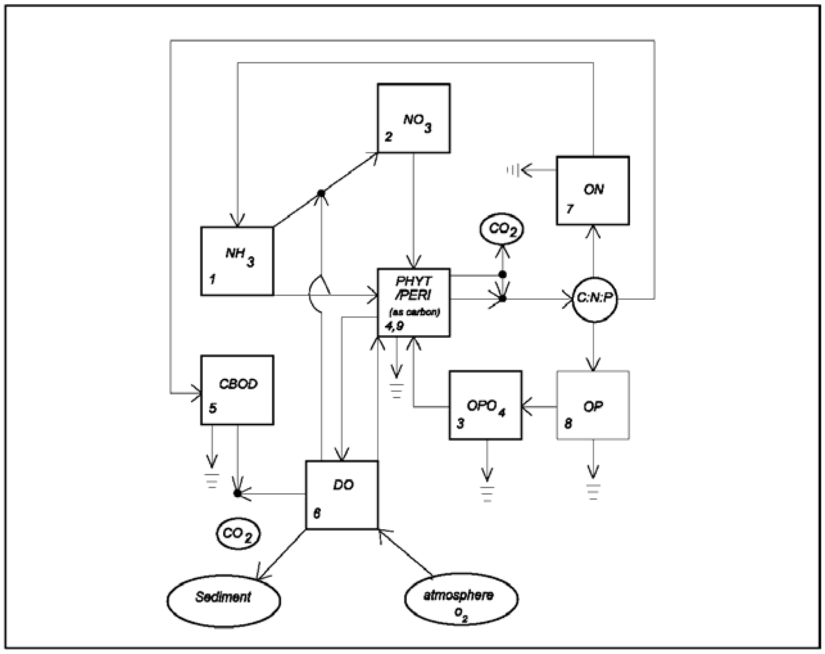


Figure 4-1: EUTRO Sub-routine Schematic

Phytoplankton/Periphyton

Phytoplankton carbon and periphyton carbon are two separate storage variables that represent the amount of carbon found in the system as algae, which drive diurnal variations in dissolved oxygen concentrations over the course of a day. Phytoplankton are free-floating algae found in the water column while periphyton are attached to the river bed preventing them from being transported downstream.

The amount of algae (in both forms) in the river depends on three processes: growth, death, and decay. Death is represented in WASP as a first-order decay rate that may vary as a function of water temperature. Settling of phytoplankton from the water column is represented by assigning a settling rate. The model also includes a base growth first-order rate similar to the first-order rate for death. The base growth rate may vary as a function of time as well. The base growth rate may be adjusted depending on the parameters that limit growth, including the availability of nutrients and the amount of light penetrating into the river. If nutrient concentrations in the river are low, the growth rate may be limited. Further, light may limit growth in several ways. Light will not be sufficient for optimum growth during the night. During the day, the light intensity may be too low or even too high to achieve optimum conditions. The presence of algae, solids, and other constituents in the river also reduce the ability of light to penetrate over the depth of the river.

The storage variable for periphyton carbon was added in the latest version of WASP5. Although periphyton carbon was not included in the existing Lower Merrimack WASP model, it may be added for this study depending on observations from the Field Sampling Program.

Phosphorus

WASP includes two forms of phosphorus – organic phosphorus and inorganic phosphorus. Both forms can be separated into particulate and dissolved fractions. This accounts for the sorption of inorganic phosphorus to suspended solids in the river.

The phosphorus cycle is simulated as biological uptake of dissolved inorganic phosphorus by phytoplankton and return of phosphorus from the biomass to the water column as dissolved and particulate organic phosphorus and as dissolved inorganic phosphorus via respiration and mortality. Organic phosphorus in the water column is also converted to dissolved inorganic phosphorus through a simulated mineralization process. In addition to phosphorus transformation, the model can account for settling of particulate organic phosphorus and settling of inorganic phosphorus sorbed to suspended solids in the river.

Concentrations of phosphorus in the river are affected by phytoplankton growth and respiration. During phytoplankton growth, inorganic phosphorus is consumed from the river. Conversely, Respiring phytoplankton release phosphorus to the river in the form of organic and/or inorganic phosphorus. The released phosphorus is then subject to the processes described above.

Nitrogen

WASP includes three forms of nitrogen – organic nitrogen, ammonia nitrogen, and nitrate nitrogen. The model considers ammonia and nitrate to be entirely dissolved. The organic nitrogen can, however, be separated into particulate and dissolved fractions.

The nitrogen cycle is simulated as biological uptake of ammonia and nitrate by phytoplankton and return of nitrogen as dissolved and particulate organic nitrogen, and as ammonia via respiration and mortality. Organic nitrogen is converted to ammonia through a simulated, first-order mineralization process. The nitrification/denitrification process is simulated by converting ammonia to nitrate, and nitrate to nitrogen gas (in the absence of oxygen). This process consumes oxygen from the river; for every gram of ammonia that is converted to nitrate, 4.57 grams of oxygen are consumed. In addition to nitrogen transformation, the model can account for settling of particulate organic nitrogen.

Concentrations of nitrogen in the river are affected by the phytoplankton growth in the system. During phytoplankton growth, ammonia and nitrate are consumed from the river by the phytoplankton. The relative amount of ammonia and nitrate that are consumed is based on model input parameters that are used by the model to calculate the "preference" of the phytoplankton for ammonia. This can be a critical factor for dissolved oxygen concentrations in the river, because the phytoplankton consumption of ammonia will reduce the amount of oxygen that is consumed by nitrification.

Phytoplankton respiration also affects the concentration of nitrogen in the river, since respiring phytoplankton release nitrogen to the river in the form of organic nitrogen and/or ammonia. The released nitrogen is then subject to the processes described above.

Dissolved Oxygen and Oxygen Demand

Dissolved oxygen may be simulated using the Streeter-Phelps equation (for steady state design conditions), the Modified Streeter-Phelps equation, a Full Linear DO Balance, or a Nonlinear DO Balance. These methods represent varying levels of model complexity that may be used to simulate some or all of the model parameters. For example, CBOD and DO can be simulated singularly by by-passing the other parameters. The primary factors affected dissolved oxygen concentrations in WASP include:

- Reaeration (based on Covar method)
- Carbonaceous Oxidation
- Denitrification
- Settling of particulate CBOD
- Phytoplankton growth and death
- Sediment oxygen demand

4.2.2 Hydrodynamic Linkage

WASP computes time varying concentrations of simulated water quality constituents for each modeled river segment. For each model time step, WASP computes the concentration of each constituent by dividing the total mass of the constituent (typically in milligrams) by the volume of water (in liters) occupying that segment during the time step. The model is based on segmentation of the river in one, two, or three-dimensions. For the purposes of the Upper Merrimack and Pemigewasset River Study, one-dimensional analysis will be performed on the riverine segments, with the possibility of two-dimensional analysis to represent the impoundment segments. The segment delineation used in WASP will be identical to that used in SWMM (Figure 3-1).

Advective transport in WASP is simulated based on the hydraulic characteristics of each river segment. For the Upper Merrimack and Pemigewasset River Study, the flows, velocity, depth and volume of each segment for each time step will be computed using the SWMM EXTRAN block and imported to WASP. WASP requires the flow information to computer the mass of constituent transported between river segments for each model time step. Dispersive transport can be simulated in the model with calibrated dispersion coefficients. Model segments are assumed to be instantaneously and completely mixed during each time step.

The equations solved by WASP are based on the principal of conservation of mass; thus, requiring that the mass of each water quality constituent being investigated is accounted for in one way or another. WASP traces each water quality constituent from the point of spatial and temporal input to its final point of export, conserving mass in space and time. To perform the mass balance computations, WASP requires the following input.

- Simulation and output control
- Model segmentation
- Advective and dispersive transport
- Boundary conditions
- Point and diffuse source waste loads
- Kinetic parameters, constants, and time functions
- Initial concentrations

The following sections outline the plan for development and calibration/verification of the river water quality model using WASP.

4.3 Model Development

4.3.1 Advective Transport

WASP allows for advective flows for up to six transport fields – surface water, pore water, sediments (three total), and precipitation/evapotranspiration. For the Upper Merrimack and Pemigewasset River model, only surface water advection will be modeled, as described in the following section.

The hydrodynamics of the mainstem Upper Merrimack and Pemigewasset River will be modeled using the EXTRAN block of SWMM (see Section 3). The flows, velocities, depths, and volumes generated by SWMM for each segment will be input to WASP. The WASP model segmentation is based on the discretization of the river in SWMM. The linkage of SWMM and WASP follows these rules:

- WASP segments are centered on SWMM nodes
- WASP interfacial flows are represented by one or more SWMM conduits
- Nodes loaded with external flows cannot represent WASP segments

SWMM calculates flow through the conduits and volume within the nodes. WASP uses flows to calculate mass transport, volume to compute concentration, and segment depths and velocities to calculate reaeration or volatilization. Figure 4-2 provides an example of linkage between the SWMM nodes and conduits and the WASP segments.

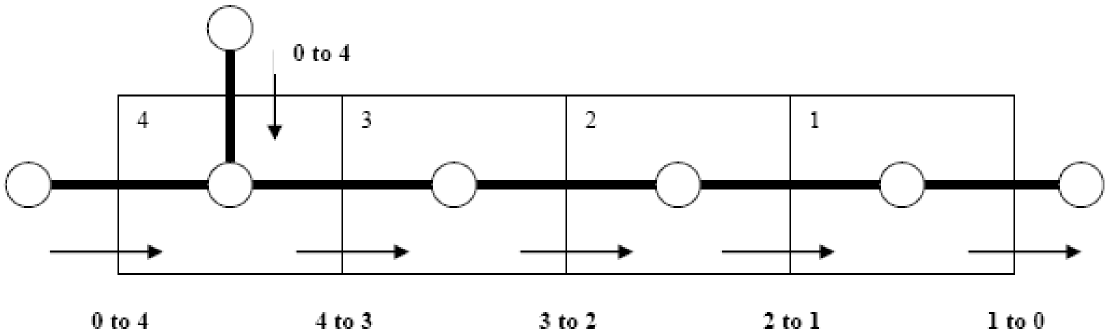


Figure 4-2: Linkage of SWMM nodes and conduits and WASP segments

4.3.2 Dispersion

Longitudinal dispersion of pollutants in the river can be modeled in WASP in two ways: using numerical dispersion to represent physical dispersion; and using physical dispersion coefficients. Numerical dispersion is a residual effect of discretizing the river – as pollutants are introduced, small impacts are distributed downstream more quickly than they would actually occur because the computation of concentration in each downstream segment is a function of the concentration in the segment immediately upstream (the backward-difference solution). Numerical dispersion can be controlled to a limited extent in WASP by increasing the timestep and by shifting from a backward-difference solution toward a centered-different solution, though the risk of model instability increases. However, it is possible that the numerical dispersion in the model will mimic the physical dispersion of pollutants in the river, and this effect will be investigated before physical dispersion coefficients are assigned. (This was found to be the case in the MRWA study).

4.3.3 Boundary Conditions

Model boundaries consist of those segments that import, export, or exchange water with locations outside the model network. Table 4-1 provides a summary of the flow exchanges and associated flow generating mechanisms.

Table 4-1: WASP Model Boundary Conditions

Flow Exchange	Flow Generating Mechanism
Upstream model boundary	HSPF
Tributaries	HSPF
Mainstem corridors	HSPF
WWTFs	Daily Records
Withdrawals	Withdrawal point operating rules and/or daily records
Downstream model boundary	SWMM

In addition to flows at the model boundaries, WASP requires an associated concentration for each system. All loads, except those from WWTFs, originating from the flows listed in Table 4-1 above will be input to the WASP model. WWTF loads will be input directly into the WASP model as point source loads.

4.3.4 Point and Non-point Source Loading

In addition to the specification of flow and concentrations at the model boundaries, WASP accepts point and non-point source loads. Loads are added to the system in constituent mass per time unit. It is important to note that loads do not have to be accompanied by flow.

WASP allows for both manual input of point source loads to the network in addition to automatic import by loading an external data file. For the purposes of the Upper Merrimack and Pemigewasset River model, all point source loads (WWTFs) will be input directly into WASP, using values based on NPDES sampling, literature values, or sampling data from the Field Sampling Program. Non-point source loads generated by HSPF will be input to WASP using a data file.

4.3.5 Water Quality Parameters

In WASP, water quality parameters are spatially-variable characteristics of the water body that may vary from one model segment to another. There are a total of 12 parameters available in the EUTRO subroutine. Table 4-2 provides a summary of those parameters that will be specified in the WASP model developed for the UMPR study.

Table 4-2 Water Quality Parameters for the Merrimack River Model

Parameter	Function	Data Source	Units
TMPSG	Segment temperature	Vary monthly	°C
KSEG	Light extinction coefficient	Calculated based on Secchi Disk measurements	m-1
SOD1	Sediment Oxygen Demand	Variable along mainstem, based on monitoring	g/m2-d
SODTA	Temperature correction coefficient for SOD	Constant based on literature values	
REAER	Reaeration coefficient	Calibration parameter	

4.3.6 Temperature

Monthly temperature values will be developed for May to October based on the water quality surveys conducted during the Field Sampling Program. The measured values will be averaged spatially and temporally before input to the WASP model. Winter month simulations will use temperature values from near-by meteorological stations.

4.3.7 Light Extinction Coefficient

The light extinction coefficients, which affect the penetration on light into the river, will be calculated using the Secchi disk measurements collected during the Field Sampling Program water quality surveys. The following methodology, outlined in Chapra (1997) will be used:

$$k_{wc} = \frac{1.7}{SD} - 0.03 * Chla$$

where k_{wc} = non-phytoplankton light extinction coefficient; SD = Secchi disk depth, in meters; Chla = Chlorophyll-a concentration, in µg/L.

The light extinction coefficient will be calculated for each mainstem sampling station during the respective water quality survey. The averages of these values will be used in corresponding WASP model segments.

4.3.8 Sediment Oxygen Demand and Sediment Nutrient Flux

Values for sediment oxygen demand (SOD) and sediment phosphorus flux (P flux) will be assigned based on the results of the sediment analysis conducted as part of the Field Sampling Program. Throughout a river reach, SOD and P flux can vary unpredictably, and accurately representing those conditions in each individual model segment is difficult. SOD and P flux constants will not be varied arbitrarily between model segments in order to arrive at the best dissolved oxygen calibration for the WASP water quality model. Rather, after gaining a general understanding of the SOD and P flux conditions throughout the mainstem, values will be assigned globally or regionally. For example, if results of monitoring show a trend of higher SOD within impounded reaches, those regions of the model will be assigned different SOD values than riverine regions that have shown lower SOD. In this way, modeled SOD will be a general representation of the conditions in the Upper Merrimack and Pemigewasset River, based entirely on field sampling of the actual existing conditions. P flux measurements in the river may show significant seasonal variability, which can be handled in WASP be specifying time-dependant functions for P flux constants.

4.3.9 Reaeration Coefficient

Unless otherwise specified by the user, WASP will explicitly calculate the flow-induced reaeration based on the Covar method, which calculates reaeration as a function of velocity and depth by one of the following three methods – Owens, Churchill, or O'Connor-Dobbins – depending on the depth of the segment. The user may, however, define a reaeration coefficient for each segment that will override this internal calculation. This will likely need to be done in the WASP model developed for the Upper Merrimack and Pemigewasset River downstream of the six dams, since WASP does not explicitly account for the reaeration of flow over dams.

Because of their greater depths, the Covar method is not a valid approach for calculating reaeration in impoundments. An alternative reaeration model will be selected and applied to the impounded reaches.

4.3.10 Water Quality Constants

In WASP, some model input parameters are assumed to have the same value for all model segments. These constants typically include parameters such as first-order decay rates and settling rates. For the EUTRO subroutine, 42 constants are available for the full eutrophication simulation. Table 4-3 provides a summary of the model constants that will be used for the Upper Merrimack and Pemigewasset River water quality model.

Table 4-3: Water Quality Constants for the Upper Merrimack and Pemigewasset Model

Model Constant	Unit
Ammonia-N	
Nitrification rate	day^{-1}
Nitrification temperature correction coefficient	---
Phytoplankton	
Phyto base growth rate	day^{-1}
Phyto growth temperature adjustment coefficient	---
Phyto carbon-to-chlorophyll-a ratio	mg/mg
Saturation light intensity	Langleys/day
Nitrogen half-saturation coefficient	ug/L
Phosphorus half-saturation coefficient	ug/L
Phyto respiration rate	day-1
Phyto respiration rate temperature correction coefficient	---
Phosphorus-to-carbon ratio	mg/mg
Nitrogen-to-carbon ratio	mg/mg
CBOD	
Deoxygenation rate	day^{-1}
Temperature coefficient for deoxygenation	---
Organic Nitrogen	
First-order mineralization rate	day^{-1}
Temperature coefficient for mineralization	---
Organic Phosphorus	
First-order mineralization rate	day^{-1}
Temperature coefficient for mineralization	---

Rate values for nitrogen and phosphorus will be based on literature values and a comparison of measured and modeled in-stream concentrations during the calibration process; the temperature correction factors will be based on typical literature values.

There are a number of constants for phytoplankton, which impact not only in-stream phytoplankton concentrations, but also the concentrations of nitrogen, phosphorus, CBOD, and dissolved oxygen. The constants that most directly affect the in-stream phytoplankton concentrations include the base growth rate, the respiration rate, the temperature correction factor for growth and respiration, the saturation light intensity, and the nitrogen and phosphorus half-saturation coefficients. The saturation light intensity and the half-saturation coefficients are use to determine the actual growth rate (*i.e.* how optimum (base) growth rate is reduced by light and/or nutrient limitations). The carbon-to-chlorophyll ratio is used to determine the quantity of oxygen that is produced by photosynthesis and the quantity of CBOD produced by respiration. The nitrogen-to-carbon and phosphorus-to-carbon ratios dictate the quantity of inorganic nutrients that are consumed during photosynthesis and the quantity of organic nutrients released by respiration. The nitrogen half-saturation constant is also used to determine the preference of phytoplankton for ammonia nitrogen over nitrate. This affects the amount of oxygen released during photosynthesis, because oxygen is released when phytoplankton uses nitrate, but is not released when the phytoplankton uses ammonia nitrogen.

As discussed above, periphyton carbon may be added to the model if it is determined that periphyton are relatively abundant and/or an important component of the river ecosystem. Results from the Field Sampling Program will be considered to make this determination.

4.3.11 Water Quality Kinetic Time Functions

In WASP, water quality kinetic time functions are model input parameters that can vary from one model segment to another, and can vary over the simulation period.

For the Upper Merrimack and Pemigewasset River modeling effort, the goal will be to keep the number of time-variable functions to a minimum. The kinetic time functions that will be defined in the water quality model include total daily solar radiation (ITOT), in Langleys, the fraction of day with sufficient light for growth (F), in days; and time-variable ambient air temperature (ARTMP), in degrees C.

4.4 Model Calibration and Validation

The WASP model will be calibrated using water quality measurements collected during implementation of the Field Sampling Plan under Task Order 2 of the Upper Merrimack and Pemigewasset River Study. The sampling program includes water quality surveys under low- and high-flow conditions, impoundment studies, and continuous monitoring. The water quality surveys and continuous dissolved oxygen measurements will be the primary performance measures used to calibrate and validate the model. The water quality constituents analyzed during the surveys include nutrient concentration, dissolved oxygen levels, and oxygen demand. Other field data will be used mainly to estimate model parameters, but may also prove useful for evaluating model performance. In addition to the data that will be collected as part of the Field Sampling Plan, NHDES maintains an Environmental Monitoring Database that can be used to aid in calibration of the WASP model.

The model will be validated using the same performance measures collected during periods independent of the calibration periods.

5 References

CDM (2006a). *Simulation Model Development*. Prepared for New England District US Army Corps of Engineers. (Sponsor Communities: Manchester, NH; Nashua, NH; Lowell, MA; GLSD, MA; and Haverhill, MA)

CDM (2006b). *Final Phase I Report*. Prepared for New England District US Army Corps of Engineers. (Sponsor Communities: Manchester, NH; Nashua, NH; Lowell, MA; GLSD, MA; and Haverhill, MA)

Chapra, S. (1997). *Surface Water Quality Modeling*. Boston: McGraw-Hill.

Smith, T.E. (2002). *Travel Times and Dispersion of Soluble Dye in Thirteen New Hampshire Rivers*. U.S. Department of the Interior, U.S. Geological Survey.

Appendix A – HSPF Calibration Procedures

The following pages describe the procedures used to calibrate the hydrologic and pollutant load components of the original HSPF model. Calibration of the HSPF model for this study will be based on these procedures.

Summary of HSPF Hydrologic Calibration Technique

Prepared by Kirk Westphal
Aug 11, 2004

CDM tested the sensitivity of the Merrimack HSPF model to various model parameters. We concentrated mainly on values that cannot be easily related to physical basin characteristics (parameters which can be estimated using physical hydrography will generally be fixed or tightly bounded). Based on insights obtained into model sensitivity, guidance documents for calibrating HSPF hydrologic models, and the desire to limit the degrees of freedom of the model during calibration, the following guidelines will be used to systematically calibrate the hydrologic responses of sub-basins in the Merrimack Watershed. This guidance is intended to be used as a framework, and will be augmented with engineering judgment when necessary.

Monthly Variable Parameters:

Ideally, the number of parameters that varies by month should be kept to a minimum, and only those parameters whose variability can be physically justified should be varied. We considered the three parameters that are most defensibly varied by month:

LZETP Lower Zone Evapotranspiration Potential – The lower soil zone is a key source of water for evapotranspiration via crops and forests, and it makes sense to vary the potential throughout the growing season. We will use values established in the Charles River HSPF model as baseline values for the basin, and adjust if necessary. Any adjustments should be consistent throughout the Merrimack sub-basins to minimize the degrees of freedom afforded by this monthly variable rate (although values may be different for different land uses).

CEPSC Interception Storage Capacity – This value should be much higher when crops are growing and leaves are on the trees. We will use values established in the Charles River HSPF model as baseline values for the basin, and adjust if necessary. Any adjustments should be consistent throughout the Merrimack sub-basins to minimize the degrees of freedom afforded by this monthly variable rate (although values may be different for different land uses).

UZSN Upper Zone Nominal Storage Capacity – This parameter is often varied in winter months to simulate the reduced absorptive capacity of a frozen soil surface. Because the Merrimack model is not simulating winter conditions, we will not vary this parameter by month.

Tuning Parameters:

The following parameters will be used to tune the model performance. These values are typically not directly associated with readily quantifiable basin hydrography.

Parameter Name	Parameter Description	Typical Range	Primary Tuning Objectives
LZSN	Lower Zone Nominal Storage (inches)	3 – 8	Match annual / seasonal runoff totals
UZSN	Upper Zone Nominal Storage (inches)	~10% of LZSN	
DEEPFR	Fraction of groundwater lost to deep aquifer	0.0 – 0.2	
CEPSC	Interception Storage Capacity (inches)	0.03 – 0.20	Match hydrograph peaks
RETSC	Retention Storage Capacity (inches)		
INFILT	Index to Infiltration Capacity (inches/hour)	See below*	Match hydrograph peaks and recess.
AGWRC	Base groundwater recession constant	0.92 – 0.99	Match hydrograph recession
IRC	Interflow recession constant	0.50 – 0.70	

* *The infiltration parameter may or may not be equivalent to the field measurement of infiltration. There is very little guidance on how this parameter is to be applied, but the model is very sensitive to its value. Initial values for INFILT will be based on weighted averages of infiltration rates for the soil types in each sub-basin (one value of INFILT will be applied per sub-basin in the pervious areas – land use impacts are accounted for by dividing each subbasin into pervious and impervious fractions). If we find that INFILT is more appropriately scaled to the soil-based infiltration rates, we will apply a consistent scaling methodology throughout.*

Parameters to be fixed:

The following variables will be fixed basin-wide, based on guidance from HSPF training documents and models of similar basins:

FOREST Fraction of forest cover: Varies by land use. Values will be fixed based on calibrated HSPF models for other New England river basins.

LSUR Length of overland flow: Tests of the Merrimack model reveal that model predictions are almost completely insensitive to this value. Typical values range from 200 to 500 feet. We will use 300 feet throughout the model.

SLSUR Slope of overland flow: These values have been estimated from topographic maps of each subbasin.

NSUR Manning's 'n' for overland flow: We will use constant values based on land use from other calibrated models in New England. The model response does not appear to be very sensitive to this parameter.

KVARY Variable groundwater recession constant: This value can be applied if observed groundwater recession deviates significantly from linear reservoir theory. Initial tests suggest that groundwater outflow can most likely be simulated using linear relationships to volume, with a calibrated linear recession constant (AGWRC, described above).

PETMAX Air Temperature at which ET is reduced below maximum potential: Not applicable when snow module is not active.

PETMAX Air Temperature at which ET is reduced to zero: Not applicable when snow module is not active.

INFEXP Exponent in infiltration equation: CDM experience in other HSPF models suggests that a value of 2.0 is appropriate.

INFILD Ration of max:mean infiltration capacity: CDM experience in other HSPF models suggests that a value of 2.0 is appropriate.

BASETP Fraction of remaining ET (after higher priority sources are utilized) to be taken from baseflow: Most evapotranspiration will come from upper soil moisture and plant uptake in this basin. This value will be set at 0.

AGWETP Fraction of remaining ET (after higher priority sources are utilized) to be taken from active groundwater: Most evapotranspiration will come from upper soil moisture and plant uptake in this basin. This value will be set at 0.

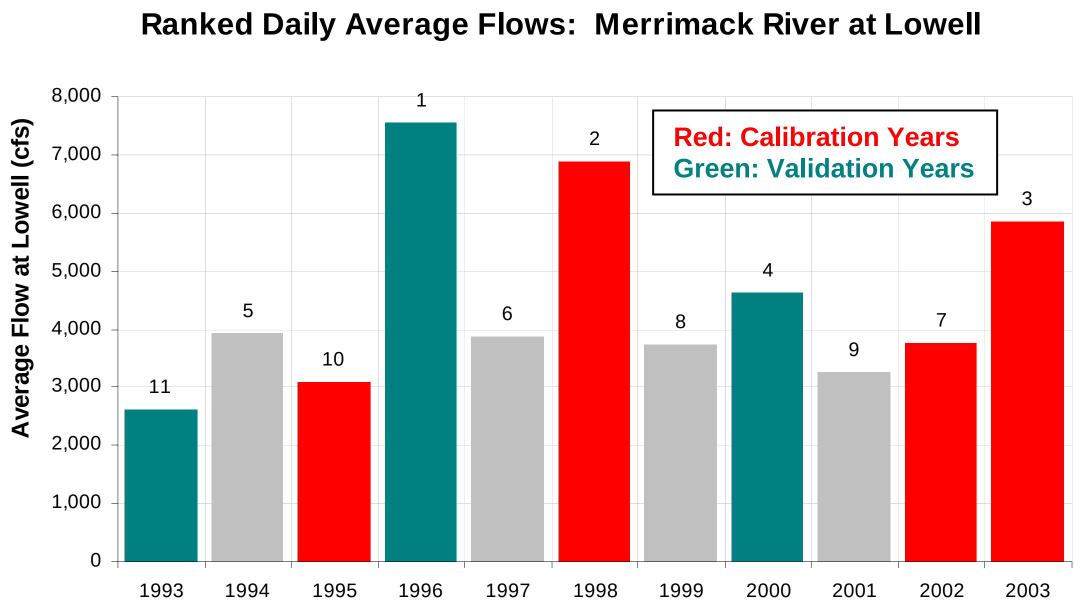
INTFW Interflow Inflow Parameter: Typical ranges are 1.0-3.0, usually toward the high end of this scale. We will use 3.0.

Calibration Periods

The model will be calibrated over the periods of record for representative dry, wet, and average years, based on total precipitation and runoff. The representative years were selected from the period of complete hydroclimatological record for the entire basin, which extends from 1993 – 2003. Regardless of precipitation or runoff volume, the model will also be calibrated to records from 2003, since this is the year in which the majority of water quality measurements were obtained.

The model will also be verified against records for representative dry, wet, and average years based on the same period of record. The figure below indicates the years that will be used for calibration and verification.

Winter months will not be simulated. The time period for each scenario will extend from April through October (inclusive). Model performance will only be measured from May through October, allowing the month of April for initial conditions to stabilize.



Calibration Performance Measures

The following types of model output will be compared to observed data to help evaluate the predictive strength of the model:

- Total runoff volume for simulation period
- Magnitude and timing of hydrograph peaks
- Shape and magnitude of receding portions of hydrograph
- Overall model fit (visual and statistical evaluation)
- Groundwater trends (relative magnitude and timing of increases/decreases in simulated groundwater volume compared to observed rise and fall of water table)
- Monthly evapotranspiration will be compared with computed potential evapotranspiration values and expected regional trends.

Summary of HSPF Pollutant Loading Calibration Technique

Prepared by Kirk Westphal
September 20, 2004

The following blocks in the HSPF code control the pollutant loading subroutines.

Pollutant Loading Parameters for Pervious Land (within PERLND):

- **NQUALS:** Number of generalized water quality constituents to be simulated in PQUAL block. (CDM has determined that 7 generalized constituents can be simulated in a single *.UCI file.)
- **QUAL-PROPS:** Specifies which generalized pollutants will be simulated, their mass units, method of simulation (constant concentration, buildup-washoff, or sediment potency), whether the pollutant is found in interflow and groundwater as well as surface flow, and whether rates are variable by month.
- **QUAL-INPUT:** Buildup and washoff parameters, capacity, and initial pollutant mass.
- **MON-POTFW –** Monthly variable washoff potency factor
- **MON-POTFS –** Monthly variable sediment potency factor
- **MON-ACCUM –** Monthly variable pollutant accumulation rate
- **MON-SQOLIM –** Monthly variable limit on pollutant accumulation
- **MON-IFLW-CONC –** Monthly variable interflow outflow concentrations.
- **MON-GRND-CONC** – Monthly variable groundwater concentrations.

Pollutant Loading Parameters for Impervious Land (within IMPLND):

- **NQUALS –** See above for PERLND
- **QUAL-PROPS –** See above for PERLND (except only option is buildup – washoff)
- **QUAL-INPUT –** See above for PERLND
- Monthly variable parameters, if any, also go into this group.

The following guidelines should be used to systematically calibrate the pollutant loading responses of sub-basins in the Merrimack Watershed. This guidance is intended to be used as a framework, and will be augmented with engineering judgment when necessary.

General Protocols:

1. Parameters should be globally based on land-use. Land-use fractions in each subbasin will determine variability in loads in different basins.
2. Parameters should be calibrated for subbasins in which water quality samples were obtained during the monitoring surveys.
3. Values should be transferred to subbasins without monitoring data by land-use similarity.

Monthly Variable Parameters:

Ideally, the number of parameters that varies by month should be kept to a minimum, and only those parameters whose variability can be physically justified and easily inferred or measured should be varied.

The following table names in the HSPF code contain parameters that may be varied by month in the HSPF model. Only those which are shaded are recommended for consideration as monthly variable values, since others cannot be confidently measured or inferred with existing data.

MON-POTFW Washoff Potency Factor for a pollutant (NOT USED)

MON-POTFS Scour Potency Factor for a pollutant (NOT USED)

MON-ACCUM Accumulation Rate (Buildup) for a pollutant

MON-SQOLIM Maximum Accumulation for a pollutant

MON-IFLW-CONC: Monthly Variable Interflow Concentration

MON-GRND-CONC: Monthly Variable Groundwater Concentration

Tuning Parameters:

The following parameters may be used to tune the pollutant load generation for generalized constituents using the buildup-washoff method. Each value for each pollutant should be bounded by literature values for the seven land-use categories used in the Merrimack model, and be applied globally throughout the subbasins by land-use.

	Parameter Name	Parameter Description	Units	Typical Range
PER	**ACQOP***	Rate of buildup on pervious land*	Lb/acre/day	[~4-14 days for full accum]
	SQOLIM	Max storage of constituent on pervious land	Lb/acre	
	WSQOP	Rate of surface runoff for 90% removal per hr	In/hour	0.5
IMP	**ACQOP***	Rate of buildup on impervious land*	Lb/acre/day	[~4-14 days for full accum]
	SQOLIM	Max storage of constituent on impervious land	Lb/acre	
	WSQOP	Rate of surface runoff for 90% removal per hr	In/hour	0.5

**These values may vary by month (see above)*

Parameters to be fixed:

The following parameters should be fixed and not allowed to vary during calibration:

SQO Initial storage of pollutant (two values for each pollutant – pervious and impervious land): These values may be adjusted as an initial condition, but should have very little (if any) impact on event responses later in the year, when the monitoring events which will be used for calibration were conducted. Generally, set at 30% - 50% of full accumulation (SQOLIM)

IOQC Constant interflow concentration.

AOQC Constant active groundwater concentration – this may vary from basin to basin, but should be fixed in each based on average observed dry weather concentrations.

Calibration Periods

The model should be run from May – October, 2003. During this period, three dry weather field surveys were conducted, and two wet weather surveys were conducted. Model performance should be calibrated to data sets from 2 of the dry weather surveys and 2 of the wet weather surveys.

Dry weather surveys were conducted on June 30 2003, August 20 2003, and September 12 2003. Each of these surveys recorded a single measurement of flow and concentration in mainstem river, and at the mouth of 11 major tributaries.

Wet weather surveys were conducted on August 22-23 2003 and September 19-20 2003. A final wet weather event is planned for 2004. During the wet-weather events, instream monitoring in the mainstem and 11 major tributaries was conducted at regular time intervals over 24 hours for bacteria (and several physical-chemical properties). Single grab samples were collected for nutrients and nutrient impacts.

Calibration Performance Measures

As a minimum, the following performance measures should be used to evaluate the effectiveness of the load generation model. Measures are listed in decreasing priority.

<u>Bacteria:</u>

1) Total mass during 24-hour storm events
2) Mass flux during dry weather
3) Total mass during 2003 season (compared to published export coefficients)
4) Timing of mass loading during 24-hour storm events

<u>Nutrients / Nutrient Impacts</u>:

1) Total mass during 2003 season (compared to published export coefficients)
2) Total mass during 24-hour storm events
3) Mass flux during dry weather

Appendix B – Channel Segmentation Maps

The following maps show the locations of all proposed and existing Lower Merrimack and FEMA transects along the mainstem of the Merrimack and Pemigewasset Rivers.