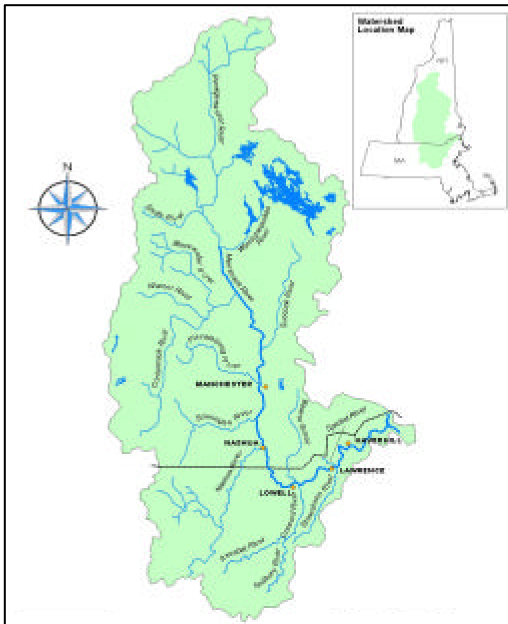


Merrimack River Watershed Assessment Study

Modeling Methodology

Prepared for:

New England District
U.S. Army Corps of Engineers

Sponsor Communities:
Manchester, NH
Nashua, NH
Lowell, MA
GLSD, MA
Haverhill, MA

March 2003

The River Basin Community Coalition concept was conceived in June 1998 in response to regulatory requirements to mitigate Combined Sewer Overflows (CSO) discharges. Because the coalition communities faced an aggregate financial commitment of 0.5 to 1.0 billion dollars, the five founding technical managers and administrators from each community believed that such an investment should be made wisely. They believed that this wise investment should be founded on good science that holistically embraces the needs of the watershed. Generally speaking the mission is to "spend smart" by making wise science based investments in activities related to water quality improvements that are not solely focused on CSO mitigation.

Executive Summary

The purpose of this Technical Memorandum is to present the modeling methodology that will be implemented in subsequent tasks of the Merrimack River Watershed Assessment Study. The results presented in this technical memorandum build upon a modeling workshop conducted on November 8, 2002, at which a general consensus was achieved on the overall modeling plan.

The underlying objective of the modeling effort is to develop a comprehensive set of models that are capable of:

- Simulating the water quality and hydraulic regimes in the mainstem Merrimack River under low-flow and baseflow conditions
- Simulating the dynamic nature of storm events and their effects on water quality and hydraulic conditions in the mainstem

Numerous models and combinations of models are capable of meeting these objectives. Following an evaluation of several models, the U.S. Environmental Protection Agency's (USEPA's) Stormwater Management Model (SWMM) and Water Quality Simulation Program (WASP) were identified as the best combination of models to simulate hydrologic, hydraulic, and water quality conditions in the Merrimack River and its watershed. Both models are capable of simulating continuous and event-based scenarios at very fine timescales (*i.e.* on the order of minutes). Additionally, both models are available through public domain.

SWMM will be used to simulate the hydrology and non-point source pollutant loading from the Merrimack River watershed, as well as the hydraulic routing in the mainstem River. SWMM was chosen for its ability to effectively model urban watersheds, which, based on a review of existing conditions, are expected to contribute the majority of pollution. CDM has also developed Combined Sewer Overflow (CSO) models for each of the five sponsor communities in SWMM, which may be linked directly to future SWMM models developed for this Study.

WASP will be used to model the water quality in the mainstem Merrimack River. WASP is capable of effectively simulating the water quality parameters of concern, including bacteria, nutrients, metals, chlorophyll-a, dissolved oxygen, and biochemical oxygen demand (BOD).

One SWMM model will be developed for the entire Merrimack River basin and will be linked directly to the WASP model developed for the mainstem. The existing CSO models for Manchester and Nashua, New Hampshire, Lowell, Greater Lawrence Sanitary District (GLSD), and Lawrence, Massachusetts, will remain separate, in order to promote manageability of the new models. The existing models will be used to generate input files for the new models at matching timescales and in compatible formats.

Contents

Preface

Section 1 - Background

1.1 Scope of Technical Memorandum 1-1
1.2 Scope of Modeling Tasks 1-1
1.3 Study Area 1-2

Section 2 - Objectives

2.1 Study Objectives 2-1
2.2 Modeling Objectives 2-2

Section 3 – Review of Modeling Workshop

3.1 Workshop Summary 3-1
3.2 Participant Feedback (Questionnaires) 3-2

Section 4 – Model Selection and Structure

4.1 Model Selection Criteria 4-1
4.2 Summary of Model Selections 4-5
4.2.1 EPA Stormwater Management Model (SWMM) 4-8
4.2.2 EPA Water Quality Analysis Simulation Program (WASP) 4-10
4.3 Linkage Strategy 4-11

Section 5 – Data Requirements

5.1 Stormwater Management Model (SWMM) 5-1
5.1.1 RUNOFF Block 5-1
5.1.2 EXTRAN Block 5-4
5.2 Water Quality Analysis Simulation Program (WASP) 5-5
5.2.1 Input Data 5-5
5.2.2 Calibration Data 5-7

Section 6 – Modeling Plan

6.1 Model Development 6-1
6.1.1 Existing Combined Sewer System Models 6-1
6.1.2 SWMM RUNOFF Model 6-1
6.1.3 SWMM EXTRAN Model 6-2
6.1.4 WASP Model 6-3
6.2 Model Calibration and Validation 6-4

6.3 Model Application and Utility 6-7
6.3.1 Existing Conditions 6-7
6.3.2 Sensitivity Analysis 6-7
6.3.3 Future Conditions Analysis 6-8
6.4 Model Output 6-8
6.4.1 Model Calibration 6-8
6.4.2 Existing and Potential Future Conditions Analysis 6-8
6.4.3 Sensitivity Analysis 6-11

Section 7 – Simulation – Optimization Link
7.1 The Theory of Optimization Modeling 7-1
7.2 Optimization Model for the Merrimack River Watershed 7-2
7.3 Plan for Optimizing Merrimack River Watershed Investments 7-4

Section 8 – References 8-1

Appendices
Appendix A: November 8, 2002 Modeling Workshop Presentation

Figures

Figure 1-1: Merrimack River Watershed 1-3
Figure 4-1: Proposed Modeling Structure for the Merrimack Watershed 4-12
Figure 6-1: Modeling Results for DO in the White River, Indianapolis, IN........ 6-9
Figure 6-2: Spatial Distribution of E. Coli in the White River, Indianapolis, IN........ 6-10
Figure 6-3: Hydraulic Profile of the Muddy River, Boston, MA 6-11
Figure 6-4: Example Sensitivity Curve 6-12

Tables

Table 1-1: Confluence of Major Tributaries in the Study Area 1-4
Table 3-1: Modeling Workshop Attendees... 3-1
Table 3-2: Modeling Workshop Questionnaire Responses 3-3
Table 4-1: Model Evaluation Matrix 4-4
Table 6-1: Data Sources for Model Calibration and Validation................................... 6-5

Section 1
Background

1.1 Scope of Technical Memorandum

The purpose of this Technical Memorandum is to summarize the modeling methodology that will be employed in subsequent tasks of the Merrimack River Watershed Assessment Study to evaluate the existing and potential future water quality and hydrologic/hydraulic conditions under various pollution abatement strategies. This report describes the scope and objectives of the modeling effort, as well as the model selection criteria, the model structure, the input and calibration data requirements, and the overall plan for model development and use. The methodology presented herein builds upon the outcome of a Merrimack River Modeling Workshop conducted on November 8, 2002 with members of the project team.

1.2 Scope of Modeling Tasks

The USACE has issued a Project Study Plan (PSP), which summarizes the proposed scope of work for 20 tasks to be completed under the Merrimack River Watershed Assessment Study. The following tasks are concerned primarily with the development and utilization of the water quality and associated hydrology/hydraulic models:

- Task 11: Develop Water Quality Models
- Task 12: River Analysis Using Developed Models
- Task 14: Alternatives Analysis

Excerpted text from the PSP defining the scope of work for each task is provided below; the proposed scope of work for Task 13: Plan Formulation is also provided, as it will be used to define the alternatives analysis performed in Task 14.

Task 11: Develop Water Quality Models

"Collect any additional data needed to set up models. Set up and run models. Calibrate and verify models for existing conditions."

Task 12: River Analysis Using Developed Models

"Use the models developed [in Task 11] to assess the relative contribution of pollutants from various sources and how the River might respond to decreases in loading from the various sources. Determine to what extent hydropower dams or other flow modifications affect the river water quality. Model results will be reviewed to determine if there are indications of other (un-modeled) sources of pollutants."

Task 13: Plan Formulation

"Develop a list of possible structural and non-structural control strategies, such as separation or treatment of CSOs, elimination of pump station overflows, reduction in illicit connections to stormdrains, and implementation of stormwater Best Management Practices (BMP's). Formulation of CSO abatement alternatives will rely on information available from communities and no new information will be developed here. Formulation of nonpoint source runoff and stormwater management BMP's will be based on the technical literature review."

Task 14: Alternatives Analysis

"Conceptual alternatives developed in the previous task (Task 13: Plan Formulation) will be analyzed using the water quality models to identify the expected water quality and ecosystem improvements associated with each alternative. Planning level costs for the alternatives will be estimated and a cost to benefit analysis provided."

Data collected during Task 10: Water Quality Sampling and Flow Monitoring will be used as input to the models developed under Task 11, as well as for calibration / validation. The water quality model will be used to simulate bacteria (fecal coliform and E. Coli), nutrients, dissolved oxygen, and specific metals if water quality exceedances are observed during the field sampling program.

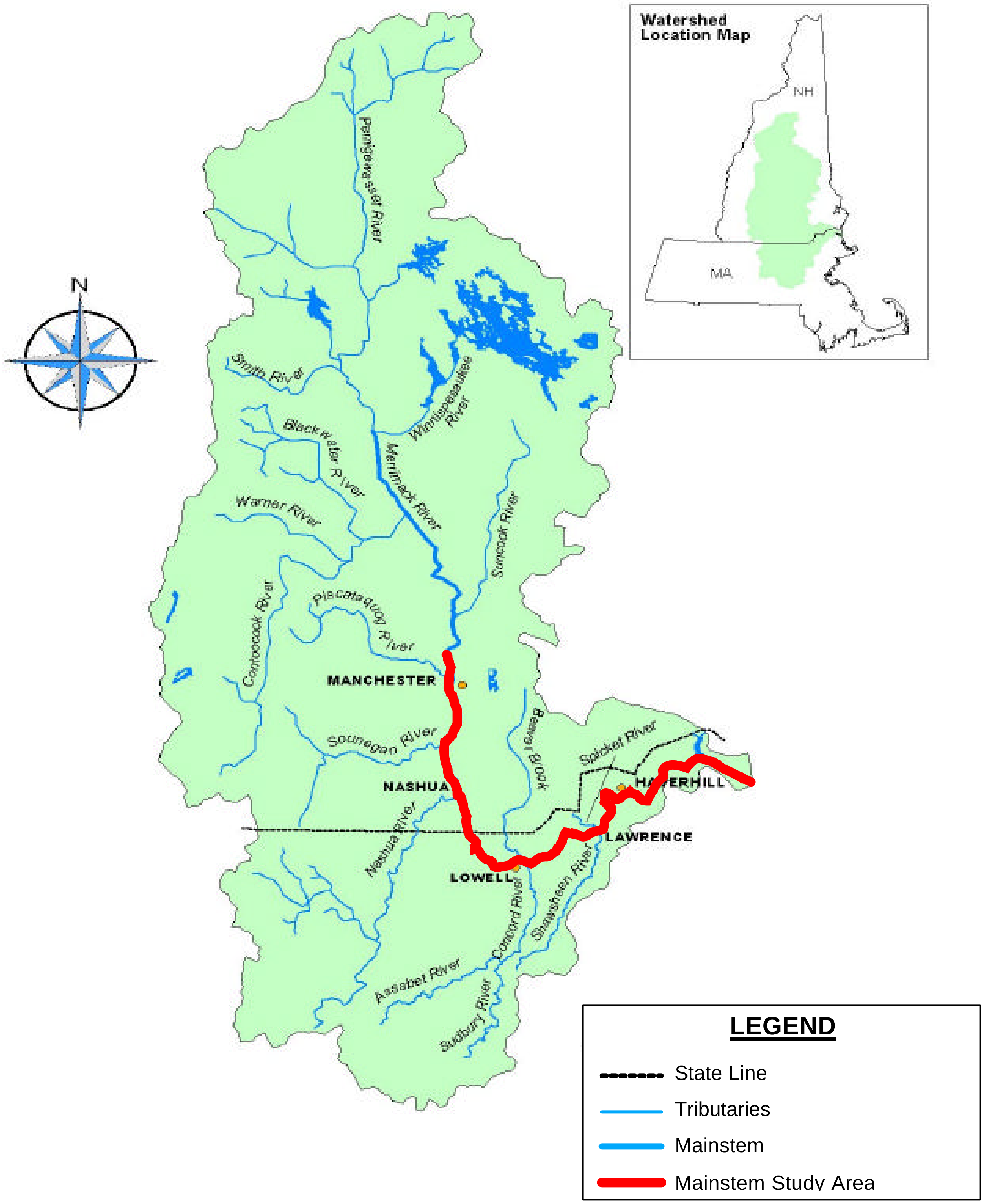
1.3 Study Area

For the purposes of the water quality monitoring and modeling efforts, the project Study Area has been defined as the portion of the Merrimack River mainstem located south of the Hooksett Falls Dam in Hooksett, New Hampshire to the mouth of the River at the Atlantic Ocean near Salisbury and Newburyport, Massachusetts. A map of the overall watershed is provided in Figure 1-1, the mainstem Study Area is highlighted in red.

This Study Area includes the five sponsor communities of Manchester and Nashua, New Hampshire, Lowell and Haverhill, Massachusetts, and the Greater Lawrence Sanitary District (GLSD), Massachusetts. Four dams are located along the mainstem Merrimack River in this area:

- Hooksett Falls Dam in Hooksett, New Hampshire
- Amoskeag Dam in Manchester, New Hampshire
- Pawtucket Dam in Lowell, Massachusetts
- Essex Dam in Lawrence, Massachusetts

Figure 1-1: Merrimack River Watershed



The watersheds of 11 major tributaries to the Merrimack River south of Hooksett, New Hampshire are also included in the Study Area (Table 1-1).

Table 1-1: Confluence of Major Tributaries in the Study Area

Location of Confluence	Major Tributary
Manchester, NH	Piscataqoug River Cohas Brook
Merrimack, NH	Souhegan River
Nashua, NH	Nashua River Salmon River
Lowell, MA	Stony Brook Beaver Brook Concord River
Lawrence, MA	Shawsheen River Spicket River
Amesbury, MA	Powwow River

The rationale for this Study Area delineation is based on several factors. First, the majority of the documented pollution problems within the overall Merrimack River mainstem occur in this lower reach. Based on a review of the Massachusetts and New Hampshire 1998 303(d) lists prepared pursuant to the Clean Water Act, only two of the 13 total listed River segments occur upstream of Hooksett, New Hampshire. Furthermore, this Study Area delineation brackets the five sponsor communities, providing a baseline water quality signal in the River upstream of the first CSOs in Manchester, New Hampshire and a comprehensive assessment of the downstream impacts of these and other pollutant sources. Additionally, this segment of the River encompasses all of the designated uses observed in the basin, including drinking water supply, hydropower, recreation (swimming and boating), and aquatic life / habitat. Finally, this Study Area definition was outlined by the USACE and sponsor communities in the project scope of work as the mainstem segment of interest.

Section 2
Objectives

This section discusses the overall study objectives, as well as the specific objectives for the modeling development and analysis tasks.

2.1 Study Objectives

The overall purpose of the Merrimack River Watershed Assessment Study is to develop a comprehensive Watershed Management Plan. The Plan will be used to guide investments in the environmental resources and infrastructure of the basin and will be aimed at achieving water quality and flow conditions that support beneficial uses, including water supply, recreation, hydropower, fisheries, and other ecological habitat. The Plan will encompass the diverse interests and goals of the various partners and stakeholders throughout the Merrimack River watershed, including state, local, and Federal governments, industry, and concerned citizen groups.

The assessment will include a water resources and ecosystem restoration investigation of the Merrimack River and will be used to answer the following questions:

1. What are the impacts of pollutants on the Merrimack River mainstem with respect to state water quality standards and hence, the designated uses of water supply, recreation, and aquatic habitat?

2. What is the relative contribution of pollutants from various sources?

3. What are the existing and potential future beneficial uses of the Merrimack River?

4. What projects or "investments" will provide the most significant return on investment?

5. Which projects should have the highest priority?

The assessment study is divided into two phases, only the first of which is currently funded. The model development and analysis tasks are included in Phase I. The general purpose of each phase is discussed below:

Phase I (Funded): The primary purpose of Phase I is to identify the relative causes and impacts of pollution problems in the Merrimack River basin as they pertain to designated uses. This will be accomplished through research, field monitoring, simulation modeling, and planning-level review of alternative pollution abatement and management strategies. Ultimately, the output from Phase I should help decision-makers to understand the relative contributions of pollutants from various sources and the basin-wide impacts of these pollutants as measured against water quality standards. The sensitivity of the mainstem water quality to incremental pollutant reductions from specific sources will also be evaluated. This information will be used to guide decisions about how best to direct funding to yield the greatest overall benefits with respect to the designated uses of the River.

Phase II (Not Yet Funded): Phase II will build on the results from Phase I through additional field monitoring to investigate specific areas of interest or concern identified during Phase I. Additionally, a detailed cost-benefit analysis will be conducted for a wide array of possible abatement, control, and restoration initiatives. The simulation modeling and planning-level alternatives analysis performed during Phase I will serve as the basis for the development of optimization models during this second phase of the project. The optimization model will help to identify potential alternatives that are both economically and environmentally successful. Ultimately, the output from Phase II will be a prioritized list of recommended investments throughout the Merrimack River watershed aimed at improving beneficial uses and restoring ecosystems.

2.2 Modeling Objectives

The principal objective of the simulation modeling is to develop a comprehensive series of models for the Merrimack River watershed that are capable of the following:

- Simulating the water quality and hydraulic regimes in the mainstem Merrimack River under low-flow and baseflow conditions
- Simulating the dynamic nature of storm events and their effects on water quality and hydraulic conditions in the mainstem

Within this overriding goal, the model must have the ability to address the following sub-objectives to consider the effort a success; these tie directly into the overall study objectives discussed in Section 2.1.

- Develop water quality and hydrology/hydraulic models that are technically sound and defensible
- Perform continuous and event-based simulations of bacteria (fecal coliform and E. Coli), nutrients, dissolved oxygen, and certain metals in the Merrimack River mainstem under existing conditions and under various CSO and pollution control abatement strategies with reasonable confidence
- Simulate the relative contribution of pollutants from major sources, including CSOs, stormdrain outfalls, major tributaries, WWTPs, and nonpoint sources
- Simulate water quality and hydraulic conditions in the estuarine portion of the basin downstream of Haverhill, Massachusetts

- Simulate the sensitivity of the Merrimack River mainstem to incremental reductions in various pollutant loads, including CSOs, WWTPs, stormwater runoff, and nonpoint source pollution

- Simulate the sensitivity of water quality in the Study Area to hydropower dam operating rules

Detailed models will be developed to simulate the hydrology of the Merrimack River watershed, the contribution of pollutant loads to the mainstem from point and nonpoint sources, and the hydraulic routing and water quality of the mainstem. The Hooksett Falls Dam in Hooksett, New Hampshire will serve as the upstream boundary condition for the hydrology, hydraulics, and water quality models. Pollutant loads entering the basin upstream of this point, as well as from 11 major tributaries, will be simulated as time-variable loads entering the system. The model will simulate the hydrology of each tributary basin; however, the hydraulic routing will only be simulated in the mainstem.

The model objectives discussed above will be used as guides for the development of model selection criteria and, ultimately, for the final model identification.

Section 3
Review of Modeling Workshop

3.1 Workshop Summary

On November 8, 2002, a Modeling Workshop was held at the USACE office to achieve the following goals:

- Present modeling objectives and proposed strategy for the modeling effort
- Review the proposed water quality and flow monitoring program from a modeling perspective
- Discuss the technical and non-technical issues surrounding the monitoring and modeling programs
- Solicit responses to fundamental questions regarded in the overall modeling effort
- Achieve consensus for modeling strategy and objectives

A list of meeting attendees is provided in Table 3-1:

Table 3-1: Modeling Workshop Attendees

Participant	Organization	Role
Barbara Blumeris	USACE	Study Manager
Townsend Barker	USACE	Technical Advisor
Harold Costa	Lowell, MA	Study Management Team
Mark Young	Lowell, MA	Study Management Team
Bob Ward	Haverhill, MA	Study Management Team
Dr. Linfield Brown	Tufts University	Technical Advisor
Dr. Steven Chapra	Tufts University	Technical Advisor
Gary Mercer	CDM	Technical Project Manager
Dr. Guillermo Vicens	CDM	Technical Advisor
Kirk Westphal	CDM	Project Engineer
Beth Rudolph	CDM	Project Engineer

A copy of the presentation given by representatives from CDM is provided in Appendix A.

A consensus was achieved during the workshop as to the general objectives, scope, and plan of action for the monitoring and modeling efforts. Several valuable suggestions were provided during the workshop that will be incorporated into the field sampling program, as follows:

- Two wet-weather monitoring stations will be added to bracket the city of Concord, New Hampshire. Concord is similar in size and land use composition to the five sponsor communities, but has a completely separated stormdrain/sewer system; thus, all wet-weather inputs to the Merrimack River mainstem would be as a result of urban runoff. Data collected at these stations may be used to determine the potential impact of the five CSO communities should they separate their entire combined systems by identifying likely pollutant loading rates from an urbanized area.

- The wet-weather storm event criteria will be modified to include, at a maximum, two storm events that fall short of the proposed full-basin coverage criteria for precipitation events of greater than 0.5 inch over a period of 12 hours. Due to typical precipitation patterns in the Study Area, it is anticipated that the full-basin coverage criteria will be met generally by frontal storms occurring during the spring and fall. In order to assess the impacts of precipitation events during low-flow, summer conditions with potentially extended dry-weather conditions, events covering only a portion of the basin and/or with an expected duration of less than 12 hours will be considered.

3.2 Participant Feedback (Questionnaires)

Following the CDM presentation and open discussion, workshop attendees were asked to complete a questionnaire addressing the following issues. A summary of the attendee responses is provided in Table 3-2; the surveys were completed anonymously.

- Are the modeling objectives clear and agreeable?

- What do you perceive as the greatest value of the models that will be developed for the Merrimack River watershed?

- What will be the greatest technical hurdle(s) for the modeling effort?

- How might these hurdles be overcome?

- Aside from the technical issues, what are your greatest concerns about the overall modeling effort?

- Should the monitoring program be reshaped in any way to better support the modeling effort?

- Any other comments or suggestions?

CDM used the feedback received in the questionnaires and general modeling workshop to further develop the modeling plan. In some cases, the responses were used as justification for elements of the proposed plan.

Table 3-2: Modeling Workshop Questionnaire Responses

Question	Respondant					
	1	2	3	4	5	6
Are the objectives clear and agreeable?	--Yes	--Seems to be	--Yes- first goal is to model E. Coli under various conditions & seasons	--Yes- as best as can be for now. Still think we need to do more on use-model links.	--Yes	--Yes
What do you perceive as the greatest value of the models that will be developed?	--Synthesize measurements & allow interpolation to attain comprehensive holistic understanding of system.	--Hopefully it will serve as a guide to prioritize spending and identify benefits from that spending.	--To understand loads to Merrimack --To run abatement alternatives at various conditions and look at impact of hydropower regulation	--Improve water quality- wise investment of money to do so. --Opportunity to explore "uncertainty" in this dynamic modeling context.	--Ability to determine the relative impacts of various loadings	--Quantify trade-offs in investments for a given/ specific set of investments
What will be the greatest technical hurdle(s) for the modeling effort?	--Simulating high-flow events (also difficult to measure) --Characterizing bacterial die-off below sources	--Develop an accurate model within budget.	--Is length a problem? 80-miles? --Someone in group noted that algorithm for E. Coli not so great- will this be an issue?	--Matching the model data needs to the sampling & monitoring contraints --Data management	--Obtain a sound database to support the modeling activities	--Not too get too detailed
How might these hurdles be overcome?	--More fine sampling below sources	--Good planning	N/A	--Having data to know when it is important	--Careful planning and careful use of available budget	--Outline final report including illustrating figures before start of modeling
Aside from the technical issues, what are your greatest concerns about the overall modeling effort?	--Should be okay if expectations aren't too high	N/A	--That the methodology used be defensible at a high technical level --That methodology is acceptable to regulators and other stakeholders	--Ensure that it will result in credibily forming a "Watershed Manangement Plan" to guide investments	--How much confidence can we have in making the predictions/ drawing the conclusions we are interested in	--Will not allow enough time/effort in seeking "optimal" program
Should the monitoring program be reshaped in any way to better support the modeling effort?	--More focus on summer storms after prolonged dry-periods --More detail locally rather than trying to pin down the whole system	N/A	N/A	--Previously mentioned: convective storm events, focusing on warm weather, extending to Concord, NH	--At this point I have no particular considerations	N/A
Any other comments or suggestions?	N/A	N/A	--Not sure how estuary will be modeled	--Make sure the MB's check out for existing conditions --Strive to make calibration as simple as possible	--Project/ study are progressing well.	N/A

Section 4
Model Selection and Structure
4.1 Model Selection Criteria

Many models and combinations of models are available for simulating watershed hydrology and its effects on receiving water quality. Very few individual models account for all of the important physical, chemical, and biological phenomena that occur when rainfall infiltrates, evaporates, runs off, washes pollutants from the land, drains through natural and manmade channels, interacts with sanitary sewage systems, and accumulates more pollution from discrete point sources along its course of travel.

Selecting an appropriate model, or combination of models, for an analysis of the Merrimack River Watershed requires careful consideration of all these phenomena, as well as the necessary time scale refinement, compatibility between models used to simulate different phenomena, and matching the model precision with ultimate objectives and with the available data. Finally, in order to provide information that will be useful to planners and decisionmakers in the Merrimack Watershed, the models must produce output that is easy to interpret, suggesting a need for graphical displays.

The modeling requirements for the Merrimack River translate into the need for fully dynamic models with comparatively high temporal precision because of the nature of time-variable CSO discharges. The simulation of storm events typically requires timescales on the order of minutes, rather than of hours, days, or weeks. Additionally, to comprehensively simulate the effects of a storm from the time it starts until the River returns to its pre-storm conditions, each component of the model must be dynamic, that is, each component must be responsive to continuously changing flows and pollutant loads that vary at time scales measured in minutes. This includes the hydrologic simulation and nonpoint source mass loading, the hydraulic routing of flows through channels, and the water quality responses to continually varying flows and pollutant loads. Without fine temporal resolution, information will be sacrificed. Also, in addition to requiring event-based simulation, the modeling program requires extended runs for seasonal evaluations and low-flow analysis.

Currently, CDM maintains Stormwater Management Models (SWMM) of the CSO systems for the five sponsor communities. In order to take full advantage of these existing SWMM models, the selected models for the Merrimack River Assessment Study should be compatible with SWMM output and the associated time scale resolution so that the time variability of point loads, and their effects on water quality, can be simulated with as much accuracy as is currently possible using the existing models as input.

Based on the information collected in the "Description of Existing Conditions" report under Task Order #1, it is anticipated that the majority of the pollution, especially bacterial pollution, will come from urban sources. Specifically, CSO discharges and stormdrains will likely contribute the majority of bacterial loads to the River, and from our experience in the region, we expect that most of the nutrient loads into the rivers will come from these sources and WWTPs. It is therefore imperative to identify models that have been specifically developed to simulate urban hydrology, hydraulics, and water quality phenomena.

This realization does not preclude the need to simulate rural hydrology and nonpoint source pollution. However, because there seem to exist no models that simulate urban and rural pollution with equal rigor, we have considered the relative ability of different models to simulate urban and rural hydrology and loading patterns, and have given preference to models specifically tailored to reproduce the urban pollution patterns that we believe will dominate the Merrimack Watershed. By matching the primary focus of the models with the primary problems in the basin, we aim to maximize the value and reliability of the information generated by the models.

The CDM Project Team compiled a preliminary list of well-proven models that might contribute toward some of the modeling objectives; a matrix is included as Table 4-1. The matrix identifies eight candidate models and compares their ability to provide the necessary information in the following three categories:

- Watershed Hydrology and Pollutant Loading
- River Hydraulic Routing
- River Water Quality

Models in each category were evaluated based on their ability to perform rainfall-runoff modeling and to simulate channel hydraulics, non-point source pollution, and instream water quality. More detailed information may be found on these and other computer modeling packages in Wurbs (1994) and USGS (2000).

The following questions were posed as guidelines for model selection for the Merrimack River watershed:

- Is the model capable of simulating continuous and event-based scenarios at very fine timescales (on the order of minutes)?
- Is the model tailored to emphasize urban hydrology and pollution sources?
- Can the model simulate nonpoint source pollutant loading?
- Can the model simulate unsteady flow in open channels?

- Can the model simulate instream concentrations of bacteria, nutrients, metals, chlorophyll-a, DO, and BOD?
- Can the water quality model simulate unsteady water quality conditions?
- Is the model compatible with existing CSO models?
- Can the output be easily understood and interpreted?
- Is the model compatible with Geographic Information System (GIS)?
- Is the model available through public domain?

Table 4-1: Model Evaluation Matrix

Primary Modeling Function: ⟶	***Watershed Hydrology and Pollutant Loading***			***Hydraulic Routing***			**River Water Quality**		
	SWMM RUNOFF	HSPF	WQRRS	SWMM EXTRAN	HEC-RAS	WSPRO	CE-QUAL-RIV1	QUAL-2E	WASP
Rainfall-Runoff									
Base flow simulation	Const	?	-	-	-	-	-	-	-
Continuous simulation	?	?	-	-	-	-	-	-	-
Event simulation	?	?	-	-	-	-	-	-	-
Land use input	?	?	-	-	-	-	-	-	-
Runoff methodology	kin wave	kin wave	-	-	-	-	-	-	-
Channel Hydraulics									
Continuous simulation	?	?	?	?	?	-	?	-	-
Routing or Profiles	NL res*	Kin wave	multiple	St. Ven.	Std Step	Std Step	St. Ven.	Manning	-
Trapezoidal Channels	?	?	?	?	?	?	?	?	-
Irregular X-sections	?	?	?	?	?	?	?	-	-
Time-Variable Flow	?	?	?	?	?	-	?	-	-
NPS Simulation									
Continuous simulation	?	?	-	-	-	-	-	-	-
Land Use Specialty	Urban	Rural	-	-	-	-	-	-	-
Total Nitrogen	?	?	-	-	-	-	-	-	-
Organic Nitrogen	?	?	-	-	-	-	-	-	-
Nitrite/Nitrate	?	?	-	-	-	-	-	-	-
Ammonia Nitrogen	?	?	-	-	-	-	-	-	-
Total Phosphorus	?	?	-	-	-	-	-	-	-
Organic Phosphorus	?	?	-	-	-	-	-	-	-
Orthophosphorus	?	?	-	-	-	-	-	-	-
Carbonaceous BOD	?	?	-	-	-	-	-	-	-
Suspended Solids	?	?	-	-	-	-	-	-	-
In-stream Water Quality									
Continuous Simulation	-	?	?	-	-	-	?		?
Time-Variable loads	-	?	?	-	-	-	?		?
DO	-	?	?	-	-	-	?	?	?
Total Nitrogen	-	?	?	-	-	-	?	?	?
Organic Nitrogen	-	?	?	-	-	-	?	?	?
Nitrite/Nitrate	-	?	?	-	-	-	?	?	?
Ammonia Nitrogen	-	?	?	-	-	-	?	?	?
Total Phosphorus	-	?	?	-	-	-	?	?	?
Organic Phosphorus	-	?	?	-	-	-	?	?	?
Orthophosphorus	-	?	?	-	-	-	?	?	?
Carbonaceous BOD	-	?	?	-	-	-	?	?	?
Chlorophyll-a	-	?	?	-	-	-	Algae	?	?
Suspended Solids	-	?	?	-	-	-	?	?	?
Iron and Manganese	-		?	-	-	-	?		?
Bacteria	-	?	?	-	-	-	?	?	?
Interface/post-process									
Graphical Displays	Fair	Good	Fair	Good	Good	Good	Poor	Poor	Good

* *NL Res = Nonlinear reservoir* ? = Yes Blank = No - = Not Applicable

Note: HSPF - Hydrologic Simulation Program - Fortran; WQRRS - Water Quality River-Reservoir System; HEC-RAS - Hydraulic Engineering Center River Analysis System; WSPRO - Water Surface PROfile; QUAL-2E - Enhanced Stream Water Quality Model; and WASP - Water Quality Simulation Program

4.2 Summary of Model Selections

Without developing a prohibitively costly custom model, there exists no single standard model that can fulfill all of the stated goals on its own. Several candidates that, at first, seemed likely because they are self-contained packages were discarded because we could not respond favorably to each of the above questions on their behalf. HSPF satisfies many of the technical requirements, but it was developed primarily to simulate rural/suburban hydrology and pollution, it has poor output displays (unless it is used inside BASINS), and it is extremely data-intensive and difficult to calibrate. BASINS is the Graphical User Interface (GUI) for HSPF and QUAL-2E.

Several USACE models were also considered. WQRRS appears to offer the hydraulic functionality needed, but because the existing CSO models are developed in SWMM, handling the interface between the different models could be cumbersome. HEC-RAS would be ideal for hydraulic analysis of the River and its tributaries, but would require at least two additional models for hydrology, loading, and instream water quality. HEC-5Q (not included in Table 4-1) also has much of the functionality desired for this project, but it is primarily intended for analysis of reservoirs and downstream flows. CE-QUAL-W2 was also found to have numerous capabilities with respect to hydrodynamic and water quality simulation; however, it was not chosen for the following two reasons: (1) while the model is capable of two-dimensional simulation (longitudinal and vertical), it assumes lateral homogeneity and we chose to reserve the ability to simulate lateral variability for in-stream pollutant concentrations, and (2) the model would require additional data processing to input the results from the existing CSO models.

CDM has developed CSO models for all cities in the Merrimack Watershed using SWMM. Based on the above criteria, and considering the fact that all cities in the watershed have CSO models developed with SWMM, we have selected the combination of the U.S. Environmental Protection Agency's (USEPA) SWMM (RUNOFF and EXTRAN blocks) with the USEPA WASP to model the Merrimack River and watershed. The models are discussed below and in Sections 4.2.1 and 4.2.2.

We selected these two models because we could answer all of the guidance questions (from Section 4.1) favorably on their behalf, and for several other important reasons, all of which are stated below:

Is the model capable of simulating continuous and event-based scenarios at very fine timescales (on the order of minutes)?

Both SWMM and WASP can simulate continuous and event-based scenarios. Both models can be programmed with very small time steps (minutes are usually reasonable for storm events) to match the resolution of input and calibration data, and to provide information about the time variability of system responses with as much resolution as possible.

Is the model tailored to emphasize urban hydrology and pollution sources?
SWMM is superior to HSPF, and nearly all other models, in simulating urban runoff. Based on our knowledge of the Merrimack Watershed, it is extremely likely that urban pollution (CSOs, WWTPs, stormdrains, urban runoff) is the dominating factor in the watershed.

Can the model simulate nonpoint source pollutant loading?
The RUNOFF block of SWMM can be used to simulate urban and rural hydrology, and nonpoint source loading. The SWMM model bases its estimates of non-point source loading on up to ten different land uses in each sub-basin, each of which can be associated with loading rates based on literature values, regional characteristics, or calibration parameters. Load rates are aggregated in the SWMM input files into a single weighted value for each subcatchment; therefore, a separate database or spreadsheet will be developed to document the specific individual loading rates for land uses within each basin. The general impact of each land use type will be evaluated by dividing tributary watersheds into subcatchments that are either dominated by a single land use or that can be effectively represented by aggregate land use parameters. Additionally, the generalized impact of point versus non-point loads will be assessed. It is not anticipated that the model will be used to develop or evaluate the water quality impacts from specific Best Management Practices (BMPs).

To our knowledge, there are no other widely used modeling packages that base non-point pollutant source estimates on more rigorous physical simulation of the source types and dispersal of pollutants through saturated and unsaturated soil zones. The other models that were considered for use in the Merrimack River Watershed Assessment Study all base their non-point source pollutant load rates on generalized land use input. As such, there would be little benefit to adding a third modeling package, such as HSPF, into the framework for the Merrimack River watershed even though it may provide some additional flexibility in evaluating the impacts of various land uses and BMPs.

Can the model simulate unsteady flow in open channels?
The EXTRAN block of SWMM can be used to route steady or unsteady flow through the mainstem. WASP can also simulate unsteady flow for water quality.

Can the model simulate instream concentrations of bacteria, nutrients, metals, chlorophyll-a, DO, and BOD?
WASP can simulate all of the necessary water quality constituents: bacteria, nutrients, metals, chlorophyll-a, DO, and BOD.

Can the water quality model simulate unsteady water quality conditions?
WASP can simulate time-variable water quality conditions.

Is the model compatible with existing CSO models?

A SWMM model of the Merrimack River can be directly interfaced with the SWMM models of the CSO systems in the cities, and the use of identical software ensures that the precision of the CSO models (which, since they serve as input, partly define the integrity of the output) is completely maintained.

Can the output be easily understood and interpreted?

Both SWMM and WASP output can be processed through commercially available post-processing programs with graphical display capabilities, including animation. Additionally, input files can be developed using graphical pre-processors.

Other reasons for the selection of SWMM and WASP:

- The combination is more cost-effective (less data intensive and cumbersome) than HSPF

- Calibrated SWMM models currently existing for the five sponsor communities of Manchester and Nashua, New Hampshire, and Lowell, the Greater Lawrence Sanitary District, and Haverhill, Massachusetts

- The two models can be smoothly integrated. Output from SWMM can easily be transferred to WASP as input with very little manipulation

- Both models are available in the public domain and widely used and supported by USEPA

- The EXTRAN block of SWMM can simulate the storage impoundments and hydraulic release structures necessary to evaluate the impact of hydropower structures on streamflow and water quality conditions

- CDM helps maintain SWMM for USEPA

- CDM has successfully used the combination of SWMM and WASP to study CSO impacts on DO and bacteria levels in the Rouge River in Detroit and the White River in Indianapolis, Indiana

- These models will support potential TMDL studies beyond the scope of Phase I

- WASP is capable of two-dimensional and three-dimensional analysis, which will be useful if we determine that lateral analysis of pollutant plumes is warranted. Our sampling program will identify the extent of lateral, or horizontal, mixing across the channel at stations downstream of point source discharges, such as CSO outfalls. The Field Sampling Plan for this program indicates that we will sample laterally across the River at selected stations downstream of certain outfalls to determine how quickly the flow becomes laterally mixed. The CDM Project Team conducted a dye study for Manchester, New Hampshire, and found that full mixing occurs within 0.5 mile of the outfall. However, generalized calculations suggest that the mixing zones may be longer for other reaches of the River. If our sampling reveals discrete plumes, we will simulate these areas with two dimensions instead of one.

- The combination of models will be able to simulate seasonal effects of various control and restoration measures, and we will be able to identify likely impacts to habitats in and along the River

In summary, the combination of SWMM with WASP will offer a comprehensive assessment of the Merrimack River watershed, will be more manageable than other alternatives, and will provide scientific output displayed in understandable, graphical formats. All of these factors will help to promote informed decisions. The CDM Project Team feels that the combination of SWMM (RUNOFF and EXTRAN) and WASP is the best choice for meeting the needs of the study with respect to the Merrimack River for the following reasons:

- *They are comprehensive*: All required conditions, scenarios, and constituents can be simulated with high resolution.

- *They are manageable*: They are easily linked together, they can interface directly with existing CSO models, they are less data-intensive than other models with comparable capabilities, and they both have graphical post-processors.

- *They are targeted*: While SWMM can provide accurate simulation of time-variable nonpoint source loading, its strength is its focus on urban hydrology and pollution loads. This will maximize the value and reliability of the output.

4.2.1 USEPA Stormwater Management Model (SWMM)

The model selected to simulate the hydrology, hydraulic routing, and watershed loading for the Merrimack Basin is USEPA SWMM. The current version of SWMM (4.4) is programmed in FORTRAN, but USEPA is developing version 5, which includes a reprogrammed engine in C++ and a Windows Interface. SWMM is a dynamic single event or continuous simulation rainfall-runoff model, developed primarily for urban areas. SWMM was developed for the USEPA from 1969-1971 by researchers at University of Florida, CDM, and Metcalf and Eddy, Inc. The model has been expanded and refined many times since by consulting engineers and academic researchers at Oregon State University (OSU) and other institutions. OSU and USEPA’s Center for Exposure Assessment and Monitoring distribute both the source code and the executable program free of charge.

SWMM was written as a group of independent modules, or “Blocks.” Two of SWMM's primary simulation modules will be used for this study:

- RUNOFF generates surface and subsurface runoff based on rainfall hyetographs, antecedent conditions, land use, and topography. It can simulate overland and free-flowing pipe flows. RUNOFF is typically run at a time step of several minutes. RUNOFF computes streamflow and depth using a nonlinear reservoir technique that combines the continuity equation with Manning's equation. Infiltration rates are computed using either the Green-Ampt equations or the integrated Horton equation. Water that infiltrates can be routed through saturated and unsaturated soil zones, and eventually back into the surface stream as baseflow. Snowmelt can also be simulated using procedures endorsed by the U.S. National Weather Service. Major catchments can be subdivided into subcatchments, each with input data that includes area, imperviousness, general basin slope, estimated surface roughness (Manning's "n"), a conceptual "width" of the catchment, depression storage, and infiltration parameters.

  RUNOFF can also be used to predict nonpoint source pollutant mass loads based on land use input. Loading rates are associated with particular land uses, and a buildup-washoff mass balance method is employed to estimate the timing and magnitude of loads into the stream. Stream concentration is then computed based on corresponding runoff volume, so that the model produces both streamflow hydrographs and pollutographs. The SWMM model does not simulate the instream reaction kinetics with adequate detail for this study, but these phenomena will be simulated with the WASP model discussed below.

  (Source: Huber 1995)

- EXTRAN (Extended Transport) performs fully dynamic hydraulic routing of flows in closed conduits and open channels in systems of any complexity, such as branching systems, tidally-influenced systems, regulated systems, and systems with dynamic backwater effects. EXTRAN is typically run at a time step of 15 seconds or less. The EXTRAN block accepts streamflow hydrographs from the RUNOFF block as input, and routes the flow dynamically using an explicit finite-difference solution of the St. Venant equations.

  (Sources: Huber 1995; DeVries, J.J., T.V. Hromadka 1993)

Version 4.4 of the SWMM model has very limited display graphics. However, USEPA is currently developing a graphical Windows interface for version 5. We will likely also use additional pre- and post-processing tools that are commonly employed to provide graphics for model input and output. MikeSWMM (DHI Inc., Trevose, Pennsylvania) provides a comprehensive interface for developing SWMM input files and viewing model output (static and animated). It is important to note that, unlike SWMM, MikeSWMM is not a public domain model. However, it will only be used for model development and graphical post-processing of the model results; the SWMM model will be fully executable without the MikeSWMM interface.

MTVE (10 Brooks Software Inc., Ann Arbor, Michigan) provides a comprehensive interface for model calibration and viewing model output. ArcView (ESRI Inc., Redlands, California) GIS software can be used to delineate stormwater catchments and to view model input and output data.

4.2.2 USEPA Water Quality Analysis Simulation Program (WASP)

The model selected to simulate receiving water quality in the mainstem Merrimack River is USEPA WASP Version 6.0. WASP was developed for USEPA and is publicly available free of charge.

The WASP model includes three submodels, two for water quality simulation (EUTRO and TOXI) and one for hydrodynamic simulation (DYNHYD). Since the Merrimack Study will rely upon SWMM for all hydraulic simulations, only the water quality modules of WASP will be utilized for this study.

- EUTRO will be used to simulate the fate and transport of nutrients, chlorophyll-a, BOD, and dissolved oxygen in the water column. The model is based on segmentation of the River in one, two, or three dimensions, and simulates the advection, dispersion, and reactions of the listed water quality constituents, including the nitrogen and phosphorus cycles.

  Advective transport is simulated based on the hydraulic characteristics of each River segments as computed using the SWMM EXTRAN block. Output from the SWMM EXTRAN block will specify flow rate, velocity, depth, and volume of each segment for each time step. Dispersive transport will be simulated with calibrated dispersion coefficients.

  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.

  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 mineralization process. The nitrification/denitrification process is simulated by converting ammonia to nitrate, and nitrate to nitrogen gas (in the absence of oxygen).

Dissolved oxygen is 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.

(Source: Wool *et al.* No year given)

- TOXI will be used to simulate the fate and transport of bacteria, and if deemed necessary, metals. Bacteria die-off will be simulated with lumped first-order decay rates. The lumped decay rates will aggregate all of the loss mechanisms into a single effective decay rate that will be allowed to vary spatially based on observed patterns.

  (Source: Wool *et al.* No year given)

The WASP model discretizes a river into numerous completely mixed elements, either in one dimension, two dimensions, or three dimensions. Several graphical pre-processors and post-processors are also available: The WASP program is distributed with tabular and graphical post-processors. WISP, which is also distributed with the model, is a menu-driven pre- and post-processing program. WASP is also available in a Windows format (WIN / WASP+ from AscI Corporation), which includes a pre-processor, analytical engine, and graphical post-processor.

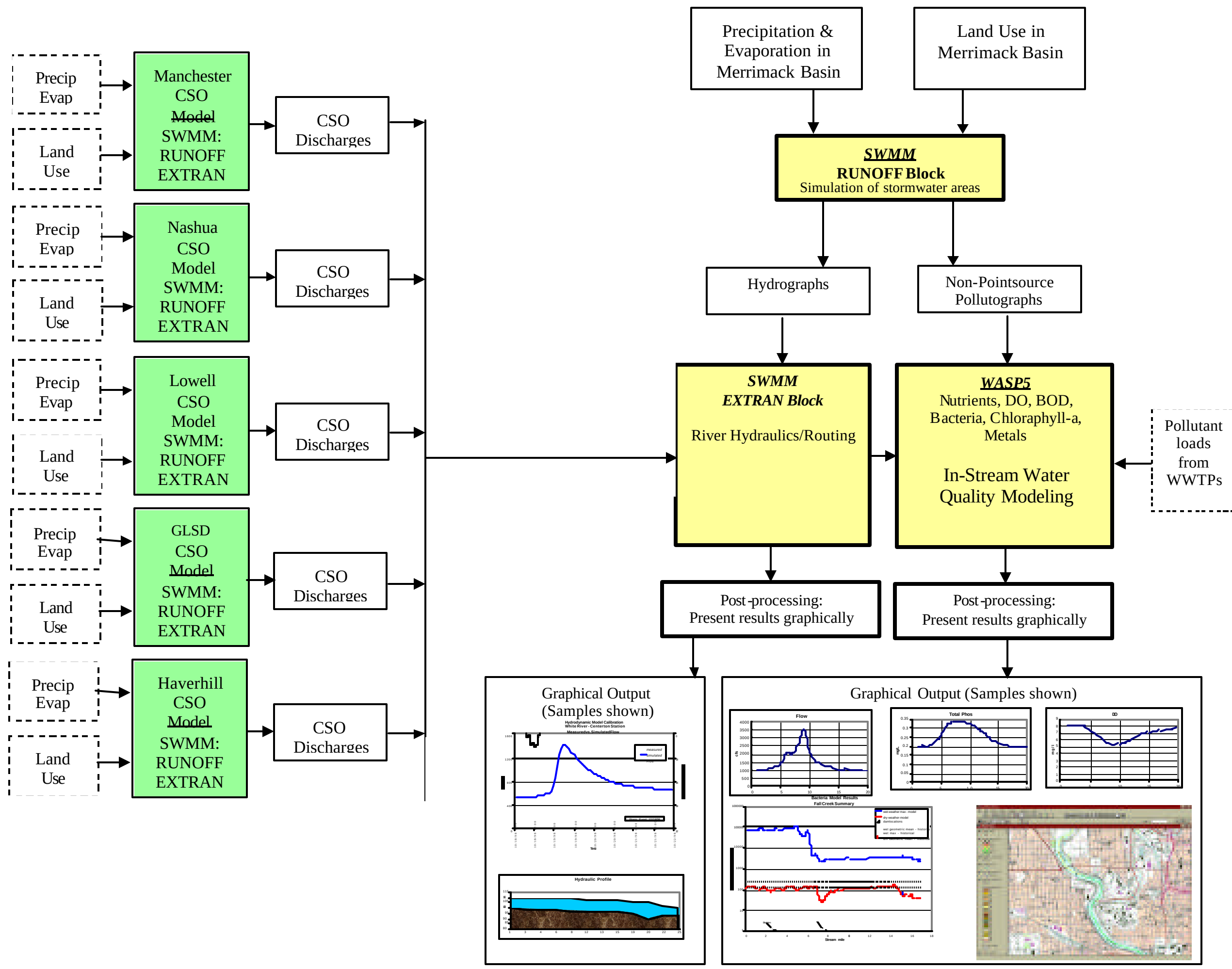
4.3 Linkage Strategy

Dividing the watershed model into discrete spatial submodels would make continuous modeling very difficult, since there are so many cause-and-effect relationships that would have to transfer from one modeling exercise to the next. Since the existing CSO models produce manageable output for specific point source locations that can easily be converted to input to a receiving water model, we feel that the best technique for simulating the entire watershed is to model the watershed in its entirety (one SWMM model for the entire basin linked with one WASP model for the entire main stem and major tributaries). The CSO models will remain separate, in order to promote the manageability of the new models, and will be used to generate input files on matching timescales and compatible formats.

Figure 4-1 illustrates the linkage between different model elements. The existing CSO SWMM models will be maintained as separate models with localized input of precipitation, evaporation, and land use / drainage characteristics. Each model will produce output files with volumetric discharge by outfall for each time step. Each outfall will be simulated in the watershed EXTRAN model as a single source of flow, and in the WASP model as a single point source of pollutant load.

The SWMM RUNOFF model of the entire watershed will be subdivided, likely into sub-basins corresponding to the major tributaries. The output of the RUNOFF module will become input to the EXTRAN module, which will simulate the hydraulic routing of the runoff flows. The RUNOFF module will also generate nonpoint source pollutant load input for the WASP model. The EXTRAN module will be linked to the WASP model by supplying the flow rates and element volumes as input data that will govern simulated transport times and dilution volumes.

Figure 4-1 Proposed Modeling Structure for the Merrimack Watershed



Section 5
Data Requirements

The following section describes the input and calibration data requirements for the SWMM and WASP models to be developed as part of this modeling effort.

5.1 Stormwater Management Model (SWMM)

As previously discussed, two primary SWMM simulation modules, RUNOFF and EXTRAN, will be used to simulate hydrologic and hydraulic conditions in the Merrimack River watershed and mainstem, respectively. Further discussion of the input and calibration data requirements for each module is provided in this section.

5.1.1 RUNOFF Block

The RUNOFF block may be used to simulate the water quantity and quality characteristics of surface water runoff and subsurface flow in a defined basin or subcatchment. Runoff is generated from rainfall data by a non-linear reservoir technique that couples the spatially lumped continuity equation with Manning's equation for overland flow. Infiltration losses are computed using either the Green-Ampt or integrated Horton equation (Huber 1995).

Input Data

The following data are required as input to the RUNOFF module for each sub-area; a brief discussion of each element follows:

- Precipitation and evaporation data
- Drainage area
- Subcatchment width (shape factor) and slope
- Imperviousness
- Surface roughness
- Depression storage
- Soil infiltration parameters
- Nonpoint source Event Mean Concentrations (EMCs)

Precipitation Data. Historical rainfall data collected at any time-scale may be entered directly to the model for continuous or event-based simulations. Additionally, synthetic design storms based on longterm statistics may be used as model input to simulate specific events. Design events are defined by the return period of the rainfall depth and by the event duration (*e.g.*, a five-year, 24-hour event). Currently, the National Weather Service (http://www.nws.noaa.gov/oh/hdsc/studies/prcpfreq.html) recommends the use of Technical Paper 40 (TP-40) to determine the rainfall volume for specific design storms with durations between one and 24 hours. The NRCS, formerly the SCS, developed four synthetic rainfall distributions to simulate the 24-hour intensity and distribution of storm event precipitation patterns across the United States. These synthetic hydrographs may be used in combination with the design event volume (TP-40) to simulate specific storm events. The SCS Type III distribution will be used for the Merrimack River watershed.

For the Merrimack River Watershed Assessment Study, historical records from several longterm monitoring stations in the basin will be used to perform continuous simulations. Design storms will be used as necessary to evaluate the effects of extreme precipitation events, such as the two-, 10-, 50-, and 100-year events.

Evaporation data will be estimated using regional monthly rates divided into the model timesteps.

Drainage Area. Subcatchment drainage areas will be delineated and estimated in GIS using available topographic information from the state repositories, MassGIS and New Hampshire GRANIT. Basins will be defined by the following watershed boundaries within the overall Merrimack River watershed:

- Pemigewasset River
- Winnipesaukee River
- Contocook River
- Soucook River
- Suncook River
- Piscataquog River
- Cohas Brook
- Souhegan River
- Beaver Brook
- Spicket River
- Powwow River
- Nashua River
- Salmon River
- Stony Brook
- Shawsheen River
- Sudbury/Assabet/Concord River
- Merrimack River mainstem

For the mainstem Merrimack River watershed, sub-areas will be defined for each region draining to combined sewer systems, separated stormwater systems, and running-off directly into the River. For the tributaries, each watershed area will be sub-divided based on land use (*e.g.*, urban versus non-urban) and general watershed size/complexity.

Subcatchment Width and Slope. Subcatchment width is defined as the subcatchment area divided by the overland flow path length. The basin width is the least physically-based parameter and is difficult to estimate in irregularly shaped drainage area. The standard calculation method is to determine several representative flow paths and compute the average area-weighted width. Similarly, the subcatchment slope can be determined by calculating the length-weighted average.

Imperviousness. In RUNOFF, the distinction between impervious and pervious surfaces is defined by the infiltration capacity. Infiltration is assumed to be zero in impervious areas; the only precipitation losses are a result of evaporation and depression storage. Two types of impervious areas are specified in SWMM:

- *Directly connected impervious area (DCIA):* The portion of the impervious area that discharges directly to the hydraulic system (*i.e.* combined sewer system)

- *Non-directly connected impervious area (non-DCIA):* The portion of the impervious area that discharges onto pervious surfaces (*i.e.* rooftop drains that discharge onto grassy lawns)

The total impervious area is the sum of the DCIA and non-DCIA. It is common practice to enter the DCIA percentage as the imperviousness of each subcatchment, so that infiltration is calculated for both pervious and non-DCIA surfaces. The DCIA values for each sub-area are determined from land use data and typical impervious cover percentages; an area-weighted DCIA is then computed.

Surface Roughness. Manning's n values are used by RUNOFF for the routing of overland flows. Separate roughness coefficients are applied to pervious versus impervious surfaces. Typical numbers are as follows:

- *Impervious*: 0.015 (dimensionless)

- *Pervious*: 0.250 (dimensionless) or higher in heavily vegetated areas

Depression Storage. Depression storage (d_s) refers to the storage depth associated with surface depressions that are filled prior to runoff. The potential depression storage is related to the surface roughness coefficient; thus, separate values are required for pervious and impervious surfaces. Typical values are as follows:

- *Impervious*: d_s= 0.1 inch

- *Pervious*: d_s= 0.2 inch

Large-scale depression storage, such as lakes, and detention ponds may be modeled implicitly by converting the storage volume to a depth over the corresponding subcatchment area.

Soil Infiltration. In the RUNOFF module, the soil infiltration rates are simulated using either the Horton or Green-Ampt equations. Infiltration rates vary based on soil type (*i.e.* SCS Hydrologic Soils Groups A, B, C, and D), antecedent moisture conditions, rainfall intensity, and depth to water table. For the Merrimack River model, the area of each hydrologic soils group will be determined in GIS from digital soil surveys. An area-weighed infiltration rate and soil storage capacity will be determined for each subcatchment.

Nonpoint source EMCs. Nonpoint source pollution will be estimated in the RUNOFF block for sub-areas on the mainstem not contributing to the CSO/stormdrain system and for the general tributary drainage areas. Event Mean Concentrations (EMCs) will be defined for each respective land use in the sub-areas based on a review of available literature.

Calibration Data

Each of the parameters discussed above in the "Input Data" section, with the exception of the subcatchment drainage areas may be used to calibrate the model. Historical rainfall records, as well as records for events sampled during the field program will be used to calibrate the model. Additionally, parameters such as the catchment width and slope, percent DCIA and non-DCIA, pervious and impervious surface roughness coefficients, pervious and impervious depression storage, and soil infiltration parameters may be used to calibrate the models.

Streamflow generated in the RUNOFF block will be calibrated to continuous streamflow data collected by the USGS at two stations in the Study Area (see below), as well as to discrete streamflow measurements collected during the Merrimack River field sampling program.

- Merrimack River near Goffs Falls, below Manchester, NH (01092000)
- Merrimack River below Concord River at Lowell, MA (01100000)

Additional information on model calibration/ validation is provided in Section 6.2.

5.1.2 EXTRAN Block

The EXTRAN (EXtended TRANsport) module is used to perform dynamic hydraulic routing of flows in closed conduits and open channel systems, including tidally-influenced and regulated systems. This section will concentrate on the input and calibration data required for open channel systems, *i.e.* modeling of the Merrimack River mainstem, since the SWMM models of the CSO systems for each of the five sponsor communities have already been calibrated. It is anticipated that only minor updates will be required for each of the CSO system models.

Input Data

The EXTRAN module uses continuous surface runoff data generated by the RUNOFF block as input to simulate hydraulic conditions in the River channel or closed conduit. For open channel models, required input data includes:

- Channel cross-section data, including x, y, z coordinates for the channel bottom
- Manning's n value for the channel bottom and left and right overbanks
- Streamflow conditions at Study Area upstream boundary

Cross-section data used for the Merrimack River watershed will include transects collected by the CDM Project Team during Fall 2002 (per Task 3B), available cross-section data from Federal Emergency Management Agency (FEMA) flood studies on the Merrimack River, and USACE transect data collected in the tidally-influence portion of the basin downstream of Haverhill, Massachusetts. Manning's n values will be estimated based on channel descriptions provided by the CDM Project Team during the Fall 2002 surveys.

Calibration Data

Streamflow generated by the EXTRAN block will be calibrated to the two continuous streamflow collection stations operated by the USGS, as discussed above. The RUNOFF and EXTRAN blocks will be calibrated concurrently to match the timing and magnitude of the streamflow. The EXTRAN block may be calibrated by modifying the Manning's n values for channel cross-sections.

5.2 Water Quality Analysis Simulation Program (WASP)

WASP Version 6.1 (WASP6) contains algorithms for analyzing (1) Eutrophication/Conventional Pollutants, (2) Organic Chemicals/Simple Metals, (3) Mercury, and (4) Temperature, Fecal Coliforms, and Conservative Pollutants (http://www.epa.gov/OST/wqm/wasp.pdf).

5.2.1 Input Data

The equations solved by WASP are based on the key principals of conservation of mass. WASP6 traces each water quality constituent from the point of spatial and temporal input to its point of export, conserving mass in space and time. The following input data is required to perform these mass balance computations:

- Advective transport rates
- Dispersion coefficients
- Boundary conditions

- Point and diffuse source waste loads
- Kinetic parameters, constants and time functions
- Initial concentrations

A brief description of the input data required for each category is provided below.

Advective Transport. Advection results from flow that is unidirectional and does not change the identity of the substance being transported (Chapra 1997). Advective transport can be modeled directly in WASP6 or WASP6 can be linked to hydrodynamic model. For the Merrimack River model, the output from the SWMM EXTRAN module will provide input flows, volumes, depths, and velocities to the WASP6 model. When the hydrodynamic file is read-in by the WASP6 pre-processor, it will define the boundary segments and the simulation time step.

Dispersion. Dispersive water column exchanges, such as longitudinal dispersion in rivers, occur as a result of velocity differences. It can be an important process in diluting peak concentrations resulting from point source discharges. Dispersion coefficients and characteristic mixing lengths will be derived from field measurements taken downstream of point source discharges to determine the longitudinal and lateral mixing of pollutants downstream of major sources, *e.g.*, tributaries and CSO/stormdrain outfalls. Time of travel studies (Task 3B) conducted along the mainstem Merrimack River in the Study Area will also be used to determine dispersion rates.

Boundary Conditions. Boundary conditions are specified for any segment receiving flow inputs, outputs, or water exchanges from outside the network, including tributary inflows, downstream outflows, and open water dispersive exchanges. Steady or time-variable concentrations must be specified for each water quality constituent at the segment boundary. Advective and dispersive flows across boundaries are specified by the transport parameters.

Point Source Waste Loads. Steady-state or time-variable pollutant loads may be specified for each point source discharge, such as municipal/industrial wastewater discharges and stormwater outfalls. Data collected during the Merrimack River field sampling program at major tributary boundaries and representative CSO and stormdrain outfalls will be used as input to the WASP6 model. Water quality data collected by WWTPs and industrial dischargers will also be used as input to the model.

Nonpoint Source Waste Loads. Nonpoint source loads will be generated in the SWMM RUNOFF block, as previously discussed, and imported to the WASP6 model from an external file. The nonpoint source file will contain information on the time-variable pollutant concentrations for each boundary segment.

Kinetic Parameters, Constants, and Time Functions. Kinetic parameters and functions will be defined for the simulation of bacteria, dissolved oxygen, and nutrients. Initial estimates for kinetic coefficients will be obtained through a combination of direct field measurements, estimation from field data, and literature values.

Initial Concentrations. Since WASP6 is a dynamic model, initial conditions must be specified all variables in each segment. Initial constituent concentrations will be defined based on measured values at the beginning of the simulation. The product of the initial concentrations and the initial segment volumes, as provided by the hydrodynamic model, will provide the initial constituent masses in each segment.

5.2.2 Calibration Data

The WASP6 model will be calibrated to the observed water quality data collected during the field sampling program by varying the dispersion coefficients, the nonpoint source loads imported from the SWMM RUNOFF block, the kinetic parameters and functions, and the initial water quality parameter concentrations. The hydrodynamic data imported from SWMM will be pre-calibrated to continuous USGS streamflow data and discrete, measured discharge data from the field sampling program. Additional detail on model calibration/validation is provided in Section 6.2.

Section 6
Modeling Plan
6.1 Model Development
6.1.1 Existing Combined Sewer System Models

CDM has developed SWMM models of the combined sewer systems for each of the CSO community sponsors of the Merrimack Watershed Study: Manchester and Nashua New Hampshire, Lowell, the Greater Lawrence Sanitary District, and Haverhill, Massachusetts. Each of these models will be reviewed to help ensure that the most current system configurations are adequately simulated. Calibration records will also be reviewed, but it is not anticipated that recalibration will be required.

6.1.2 SWMM RUNOFF Model

A SWMM RUNOFF model of will be developed using MikeSWMM, a Windows-based pre-processor used to delineate drainage areas, specify flow paths, and write an input file for the Fortran engine. GIS images of USGS topographic maps will be displayed electronically so that basin delineation can be performed as accurately as possible. GIS coverages of land use in Massachusetts and New Hampshire will also be displayed electronically in order to specify pollutant load patterns for nonpoint sources within each subcatchment. As previously noted, MikeSWMM is not a public domain model; however, the SWMM model developed during Phase I will be fully executable without the MikeSWMM interface.

The model will be structured so that a single input file is used to simulate the entire watershed. The inflow and pollutant concentrations at the headwaters of the study area will be estimated from a single contributory catchment above Hooksett Dam.

The model will have greater resolution within the primary study area (from Hooksett Dam to the ocean). Each tributary basin will be simulated as a separate subcatchment, and each of these may be further subdivided into smaller catchments in order to adequately reproduce the timing of flows and loads, as well as the likely die-off and fate of certain pollutants as they flow toward the confluence with the mainstem. This simple routing method avoids the need for complex hydraulic routing models of the tributaries. Output of the RUNOFF model for the tributaries will take the form of hydrographs and pollutographs at the confluence with the mainstem.

Urban runoff captured by combined sewer systems will not be simulated in the watershed model, but will be simulated in the individual system models described above. Urban stormwater that drains directly to the river will be simulated in the watershed model by delineating urban subcatchments as necessary. Rather than subdivide urban areas into catchments for each individual stormdrain outfall, the resolution employed for urban stormwater drainage will be such that each major area serviced by a stormdrain system will be simulated as a single catchment, and each area will have one point of discharge into the river (it is not practical to simulate each stormdrain outfall as an isolated source, nor is it necessary for the evaluation of stormwater effects).

6.1.3 SWMM EXTRAN Model

A SWMM EXTRAN model of the mainstem channel will be developed using MikeSWMM, a Windows-based pre-processor used to specify bathymetric information and write an input file for the Fortran engine. The model will simulate dynamic routing of the hydrograph input from the RUNOFF block through the mainstem of the Merrimack River.

The model will range from the Hooksett Dam upstream of Manchester, New Hampshire to the ocean, and will simulate just the mainstem of the River. Hydrologic contributions from the tributaries will be simulated as boundary conditions at the confluences with the mainstem using the output hydrographs from the RUNOFF module (EXTRAN will not be used to simulate hydraulic routing in the tributaries). Channel geometry for the mainstem will be defined with a minimum of 100 bathymetric transect maps (Task 3B). The selected transect locations have been spaced at average intervals of roughly one-mile, and have been chosen to adequately represent constrictions, expansions, islands, etc. Each coordinate for each transect location will have vertical accuracy of ±2 cm, and horizontal accuracy of ±1 cm.

Where refinement may be needed in the model (*i.e.* at bridges), additional transects may be added based on available bathymetric data from FEMA Flood Insurance Studies (FIS's) for the mainstem. The data is available in hardcopy as printouts of original HEC-2 model input files. Also, the Army Corps of Engineers has compiled detailed bathymetric data for the reach of the mainstem from Haverhill to the ocean, and these transects may also be used to augment the EXTRAN model if needed. If FEMA or Corps data are used to augment transect data compiled as part of Task 3B of the Merrimack River Watershed Assessment Study, the data will be transposed such that it is represented with respect to a single vertical datum.

The EXTRAN model will include simulation of the four major dams on the mainstem; Hooksett Dam, Amoskeag Dam, Pawtucket Dam, and Essex Dam. The operating rules for each dam will be simulated to the greatest extent practical by translating operating logs and FERC license data into logical statements in the program code. The EXTRAN Block of SWMM is capable of simulating the hydraulic response of storage impoundments. It can also compute the hydraulic flows through release gates and spillways according to time-based or condition-based logic. It is not anticipated that the SWMM source code will need to be modified to simulate these impacts; however, if found to be necessary, any source code modifications will be fully documented in the final report.

6.1.4 WASP Model

A WASP model of the mainstem Merrimack River will be developed to model water quality. Initially, the model will be developed as a one-dimensional model – that is, the river will be segmented into individual elements, each simulated as fully mixed, and arranged in series. If results of the sampling program for the Merrimack River Watershed Assessment Study reveal that mixing zones are much longer than the length of model elements, the model may require two-dimensional discretization (lateral and longitudinal) in certain areas (through and immediately downstream of CSO communities, for example). The mainstem Merrimack River is generally 500 to 1000 feet wide. Depths behind the dams generally range from 30 to 40 feet depending on flow conditions.

It is not anticipated that vertical discretization will be required, although sampling of dissolved oxygen and temperature profiles in each of the four major impoundments may reveal stratified layers and warrant vertical segmentation of the model in localized areas. Sizing of the individual elements will be accomplished according to the following four objectives:

- Match the hydraulic segmentation of the SWMM EXTRAN model to the extent practical
- Provide sufficient resolution to simulate spatial variability of pollutant concentrations within the river
- Avoid unnecessary computational refinement
- Avoid numerical instability

Reaches listed on the 303(d) lists for both states are often quite long (on the order of five to ten miles), and to improve the utility of the models, it will be useful to divide these reaches into smaller elements in order to investigate how much of the impaired reaches may be affected by particular abatement or management programs. It is anticipated that the model will likely contain approximately 100 individual elements, and that the average length of each element will be approximately one mile. It will not be necessary to apply one uniform length to the segments. Calculations will be made to estimate the maximum allowable segment length that will avoid numerical instability or excessive numerical dispersion (erroneous results stemming from inflated numerical estimation errors that can be compounded in time and space). These calculations will account for anticipated ranges of possible dispersion rates and flow velocities. Segment lengths throughout the simulated river will subsequently be held to less than the lowest of these maximum allowable values. Resulting volumes for each segment will be computed as functions of measured bathymetry (from the SWMM EXTRAN model) and the water surface elevation.

Parameters will be entered into the EUTRO module to simulate the phosphorus cycle, nitrate/nitrite and ammonia concentrations and reactions (including nitrification), and dissolved oxygen. First-order decay rates for bacteria will be entered into the TOXI module. Rather than simulate the individual loss mechanisms for bacteria, aggregated first-order decay rate(s) will be calibrated (there may be some spatial variability of the aggregate decay rate). If monitoring results indicate the need to simulate fate and transport of specific metals, the TOXI module will be adjusted to include the physical and chemical reactions of such metals in the simulation.

6.2 Model Calibration and Validation

The individual model elements will be independently calibrated and validated to ensure that not just the end results are credible, but that the mechanisms used to simulate the system can adequately reproduce observed phenomena.

The models will be calibrated by tuning the specified parameters (see Section 5.0) within physically plausible ranges for the Northeast region until the models adequately reproduce observed timeseries, event statistics, and/or seasonal statistics. The parameters will be tuned such that the timing and magnitude of variations in state variables such as flow and concentration will be adequately reproduced. Specific attention will be paid toward accurate simulation of low-flow conditions, as predicted water quality during these conditions will be most indicative of potential use attainment.

Model validation will be accomplished using separate event records or periods of record that were not used during model calibration. In this way, the predictive strength of the calibrated models will be "tested." The validation results, more so than the calibration results, will indicate how much certainty we can place in the ultimate model predictions.

The project team, including CDM, the Corps of Engineers, and the sponsor communities, will review calibration and validation results to determine the adequacy and credibility of the models. All calibration/validation results will be included in the task order report for Task 11: "Develop Water Quality Models," along with final values of parameters compared to regionally observed ranges from the literature. The actual calibration methods will also be summarized in the report.

Table 6-1 outlines the data that will be used to calibrate and validate the models.

Table 6-1: Data Sources for Model Calibration and Validation

Model Element	Modeling Tool	State Variables	Calibration Data Source(s)*	Validation Data Source(s)*
Streamflow at tributaries	SWMM Runoff	Runoff hydrographs at confluences with mainstem	Flow rates from USGS records (where available). Field data from three of four dry weather events and two of three wet weather events.	Flow rates from USGS records (not used for calibration). Field data from remaining dry and wet weather events (one each).
Streamflow in mainstem	SWMM Runoff	Runoff hydrographs along mainstem	Flow rates and river stage from USGS records (Manchester, NH and Lowell, MA). Field data (rating curve readings) from three of four dry weather events and two of three wet weather events.	Flow rates from USGS records (not used for calibration). Field data (rating curve readings) from remaining dry and wet weather events (one each).
Tributary pollutant loads	SWMM RUNOFF	Pollutographs at confluence with mainstem for 11 major tributaries	Field data (pollutant concentrations and flow rates from rating curves) from three of four dry weather events, and two of three wet weather events.	Field data (pollutant concentrations and flow rates from rating curves) from remaining dry and wet weather events (one each).
Stormdrain pollutant loads	SWMM RUNOFF	Flow hydrographs and pollutographs from stormdrain areas	End-of-pipe stormdrain concentrations from two of three wet weather events. Runoff volume will be calculated by Rational Method.	End-of-pipe stormdrain concentrations from remaining wet-weather event. Rational method for estimate of flow volume.

Model Element	Modeling Tool	State Variables	Calibration Data Source(s)*	Validation Data Source(s)*
CSO pollutant loads	SWMM EXTRAN	Flow hydrographs and pollutographs from CSO outfalls	Models already calibrated – calibration records will be reviewed.	End-of-pipe CSO outfall concentrations. There is no good way to validate outfall flow predictions without detailed flow monitoring.
Mainstem river hydraulics	SWMM EXTRAN	River stage and velocity at selected stations	USGS depth records from Manchester, NH and Lowell, MA. Field data from three of four dry weather events and two of three wet weather events (along mainstem). Time-of-Travel studies (two reaches)- also from 1960s report, if CDM studies confirm values.	USGS records from Manchester, NH and Lowell, MA (not used for calibration). Field data from three of four dry weather events and two of three wet weather events (along mainstem). Time-of-Travel studies (same reaches as calibration, different velocities) - also from 1960s report, if CDM studies confirm values.
Mainstem water quality	WASP	Concentrations of bacteria, nutrients, DO, metals	Field data from three of four dry weather events and two of three wet weather events. Time-of-Travel studies by for dispersion.	Field data from remaining wet and dry weather events (one each).

*Field data from wet -weather events will be time-variable. Field data from dry-weather events will be discrete.

6.3 Model Application and Utility

As outlined in the scope of work for Task 12: River Analysis Using Developed Models and Task 14: Alternatives Analysis, the calibrated SWMM and WASP models will be used to evaluate the water quantity and quality response of the Study Area under existing and potential future conditions as a result of various pollution abatement strategies.

6.3.1 Existing Conditions

The calibrated models will be used to simulate the existing water quality and flow conditions in the watershed under dry- and wet-weather conditions. These results will be used to assess the attainment of water quality standards through the Study Area, as prescribed by the designed uses of the Merrimack River mainstem. The relative contribution of pollutants from various sources, such as WWTPs, CSOs, stormdrain outfalls, major tributaries, and nonpoint source pollution, will also be assessed under dry- and wet-weather conditions. Existing conditions will be evaluated for both annual and seasonal scenarios.

6.3.2 Sensitivity Analysis

A sensitivity analysis will be performed to determine the water quality response of the system to incremental reductions in pollutant loads from major sources discharging to the Merrimack River mainstem south of Hooksett, New Hampshire. The following scenarios will be evaluated:

- Reduction of CSO pollutant loads
- Reduction of pollutant loads from stormwater runoff
- Reduction of WWTPs pollutant loads
- Reduction of aggregate nonpoint source pollution, such as septic systems, animal deposition, and non-urban runoff
- Reduction of pollutant loads from major tributaries

The response of the system to the 100, 75, 50, and 25 percent reduction of pollutant loads will be simulated individually for each source listed above.

In addition, the sensitivity of water quality and flow conditions to modifications in hydropower operating rules at the Hooksett, Amoskeag, Pawtucket, and Essex Dams are planned to be assessed using the developed models. Scenarios are also planned to simulate conditions in the mainstem under the complete removal of each dam.

6.3.3 Future Conditions Analysis

The future water quality and flow conditions in the mainstem Merrimack River will be evaluated based on various proposed investment strategies developed under Task 13: Plan Formulation, including at a minimum:

- Implementation of the five sponsor community's Long-Term Control Plans (LTCPs)
- Complete separation of the combined sewer systems in the five sponsor communities
- Implementation of Best Management Practices (BMPs) to reduce pollutant loads from in USEPA Phase II Stormwater communities

The simulation results will be compared to state water quality standards and the ability of the River to meet designated use requirements under the various pollution abatement scenarios will be assessed.

6.4 Model Output

The SWMM and WASP model output will be summarized in a variety of graphical and tabular formats, depending on the scenario being evaluated.

6.4.1 Model Calibration

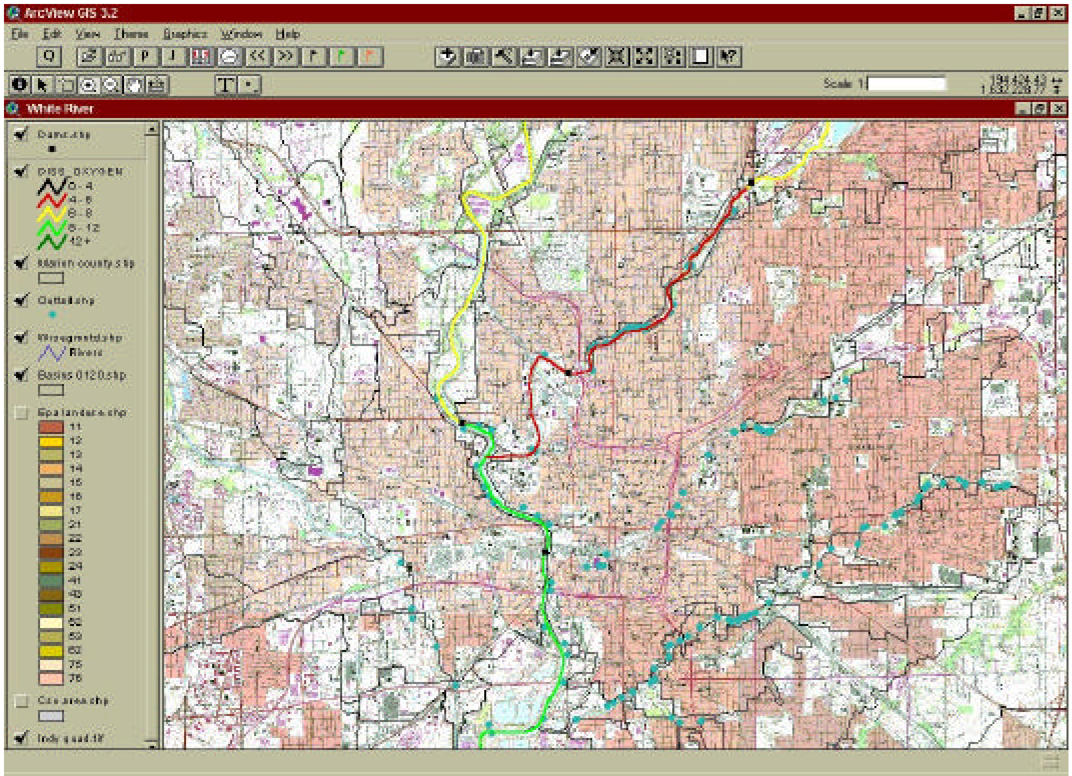
The model calibration results for SWMM and WASP will be graphically presented at stations along the mainstem where water quality and streamflow data was collected. Additional calibration curves for the hydrodynamic model will be presented at the two active USGS gaging stations along the Merrimack River mainstem.

6.4.2 Existing and Potential Future Conditions Analysis

Raw water quality data obtained as output from the analysis of existing and potential future conditions will be imported into a GIS database to facilitate the graphical presentation of data. Modeling results for each water quality constituent will be overlain on a USGS quad sheet or similar basemap to show the range of concentrations. A similar map prepared by CDM for the White River in Indianapolis, Indiana is provided in Figure 6-1.

Figure 6-1: Modeling Results for DO in the White River, Indianapolis, Indiana

SAMPLE of SWMM/WASP output is overlain as a GIS coverage.



Additional graphs developed in Microsoft Excel may be used to display pollutant concentrations versus river mile and select hydraulic profiles along the mainstem for existing and potential future conditions. Examples are provided in Figure 6-2 and 6-3, respectively.

Figure 6-2: Spatial Distribution of E. Coli in the White River, Indianapolis, Indiana

SAMPLE of SWMM/WASP output displayed on an EXCEL graph

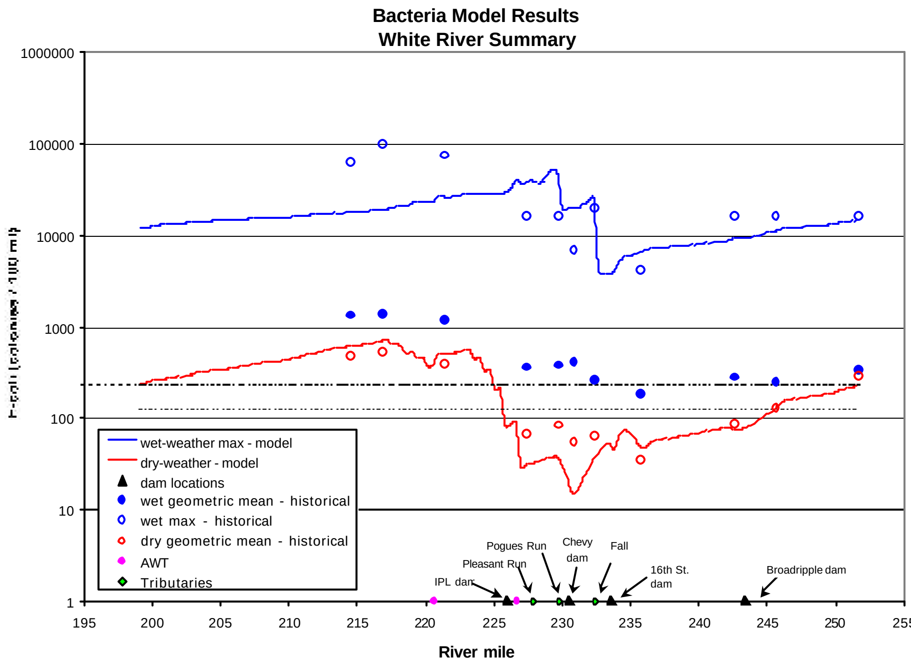
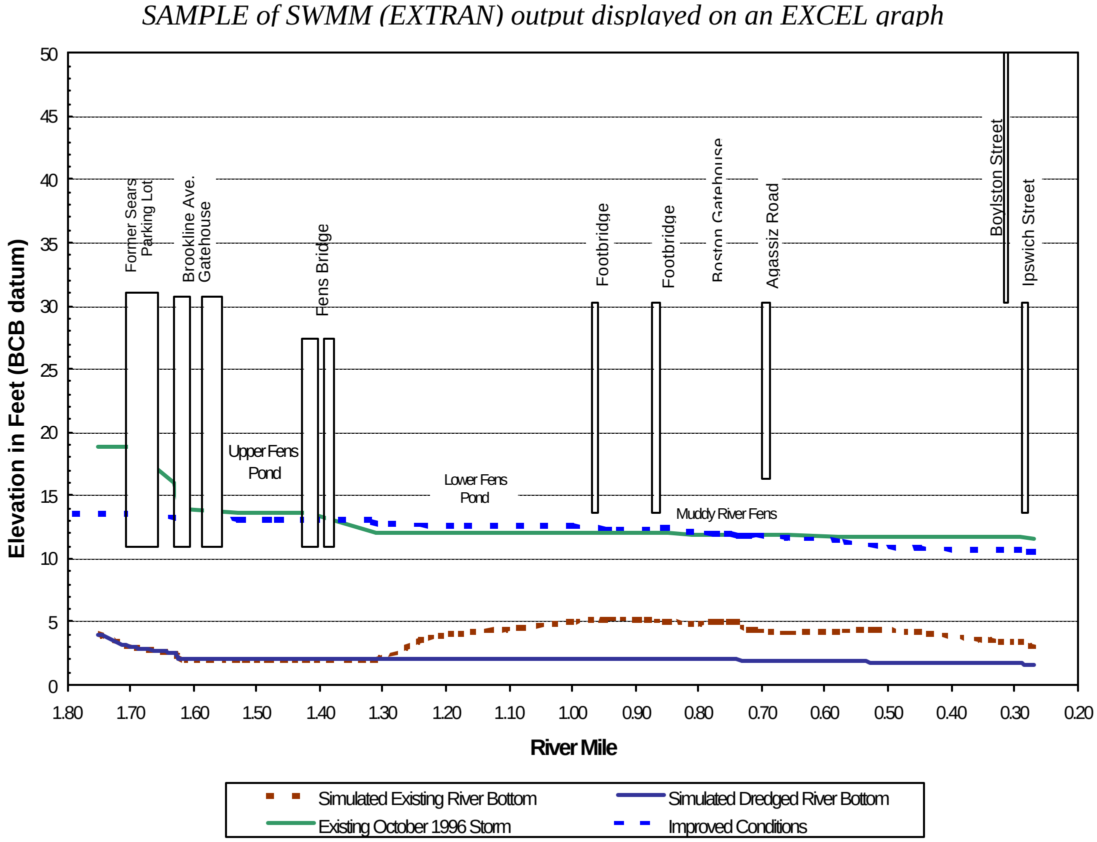


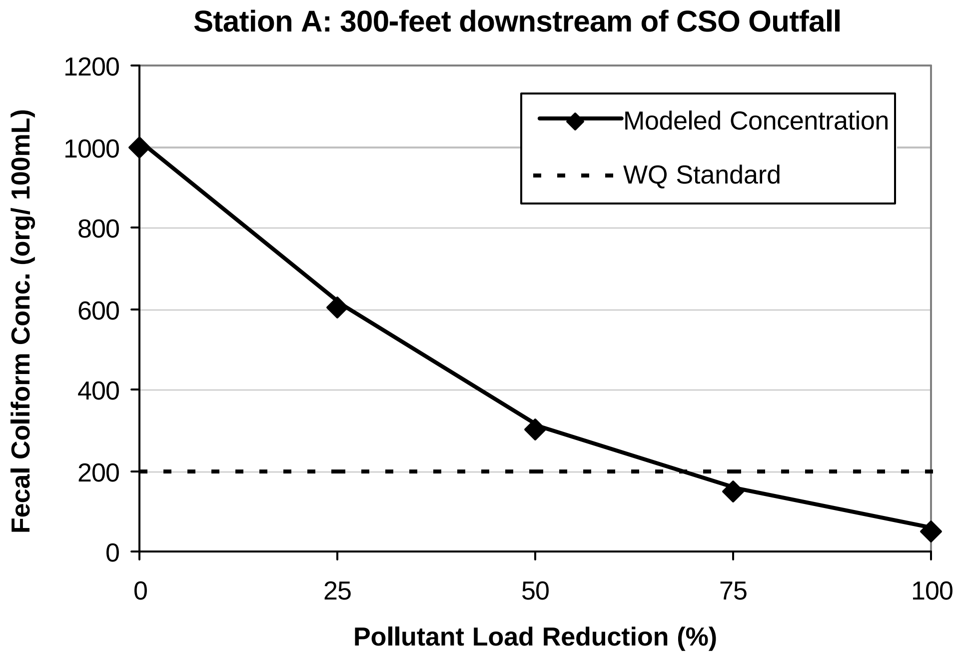
Figure 6-3: Hydraulic Profile of the Muddy River Boston, Massachusetts



6.4.3 Sensitivity Analysis

Excel charts will be developed to summarize the results of the sensitivity analysis described in Section 6.3.2 at select points in the Merrimack River mainstem. An example is provided in Figure 6-4.

Figure 6-4: Example Sensitivity Curve



Additionally, graphs displaying the pollutant concentrations versus river mile may be created similar to Figure 6-4 showing the concentrations at 100, 75, 50, and 25 percent reduction.

Section 7
Optimization Modeling Plan

The ultimate objective of the Merrimack River Watershed Assessment Study is to identify a combination of abatement and restoration investment alternatives that represent a reasonable balance between costs and environmental benefits. Investment alternatives will be identified and analyzed in Tasks 12 – 14 of Phase I of the study, and may include such measures as storage-treatment systems for combined sewer systems, improved wastewater treatment technologies, stormwater management systems, bio-uptake systems for non-point source pollution, and others. While the sensitivity of water quality to generalized investment plans will be analyzed in Phase I, a prioritized list of specific measures can only be developed with detailed subsequent analysis of economic and environmental costs and benefits, followed by a systematic, justifiable optimization process and trade-off analysis that considers the value of each alternative with respect to stated objectives and within the bounds of implementation constraints.

While simulation modeling results are basically objective, the priorities of planning objectives, and some of the perceived impacts of certain projects on habitat and ecosystems are much more subjective. Each stakeholder group will place different emphasis on the costs and benefits based on their core values. Answering questions with both objective and subjective considerations requires more than repeated simulation of the physical system, so we propose a facilitated, collaborative decision support process for prioritizing the list of projects and identifying a recommended watershed plan.

What follows is a general description of optimization modeling, and a suggested approach for including it in the Merrimack River Watershed planning process.

7.1 The Theory of Optimization Modeling

The word “optimize” is often overused, and its meaning has become generalized so that it is often used synonymously with “improve.” True mathematical optimization, however, refers to improvements to the *greatest possible extent* toward a measurable objective, subject to well defined constraints. While best practices and sound engineering judgment are often credited with system improvements, true optimization, especially within a framework of multiple objectives, often requires more complex and rigorous mathematical analysis.

The science of system optimization, originally referred to as “operations research,” but now widely known as “systems analysis,” developed partly in the manufacturing sector, as plant operators sought to streamline production of goods. Today, engineers apply systems analysis techniques in many disciplines, and the methods have seen increasing use in the water resources field, particularly for screening or prioritizing planning alternatives for multipurpose reservoir systems (Sinha *et al.* 1999; Watkins and McKinney 1999; Turgeon 1987; Randall *et al.* 1997) problems not unlike watershed management planning due to competing interests constrained by economic and environmental factors. Systems analysis has also been applied specifically to the problem of watershed management, as described by (Newbold 2002).

An optimization program contains three basic elements:

- A mathematical objective, which is to be either minimized or maximized (*i.e.* maximize the number of days in meeting water quality standards)

- A set of "decision variables" (*i.e.* investment alternatives or amounts, flow rates, load rates, etc.), which are allowed to vary until the mathematical objective reaches a maximum or minimum value

- A set of constraints that bound the values of the decision variables and create a multi-dimensional "decision space" based on physics, regulations, economics, and politics (*i.e.* treatment technology A = $X per million gallons or storage in system B ≤ Y million gallons)

The goal of an optimization model is to find the combination of decision variables values that either maximizes or minimizes the value of the objective function inside the set of constraints. Several widely used "search" algorithms (*i.e.* the Simplex algorithm, gradient search algorithms, and evolutionary algorithms) have been developed to solve such problems systematically and efficiently. The increased accessibility of these tools, as a result of computing advances, has led to the increased use of optimization programs for water resource planning projects. This is especially true in situations where stakeholders have multiple objectives and when the alternatives are too numerous to prioritize through pure enumeration.

7.2 Optimization Model for the Merrimack River Watershed

For the Merrimack Watershed Assessment Study, the problem (in simplified form) is to select the combination of abatement and restoration investments that best satisfies the following objectives:

- **Maximize** the number of segment-days during which water quality standards are met

- **Maximize** the environmental benefits associated with different investments (such as additional acres of wetland, additional days that waters designated as fisheries meet standards, additional reaches that can be made suitable for drinking water supply, etc.)

- **Maximize** the economic benefits associated with different investments (such as an improved commercial shellfishing industry, additional recreational revenues, improved hydropower production balanced with flow and temperature requirements)

- **Maximize** the net cost:benefit Ratio such that target levels of water use are achieved

Subject to constraints, such as:

- Economic costs of implementing abatement or restoration alternatives
- Physical constraints such as available flow, residual pollutant loads, and sensitivity relationships between investments and water quality improvements (developed as part of Task 12)
- Stakeholder preferences
- Satisfying regulatory standards for water supply
- Satisfying regulatory standards for shellfish beds
- Satisfying regulatory standards for recreational uses
- Satisfying regulatory and ecologic standards for fish
- Maintain adequate hydropower revenues
- Achieving measurable ecosystem improvements

In its fully expanded formulation, the problem will likely include hundreds or thousands of decision variables (each specific alternative, and potentially each level of implementation of each alternative will be a unique decision variable). The problem will also include hundreds or thousands of constraints, since the river system will be segmented longitudinally and because the optimization problem will be considered in a temporal framework with numerous timesteps (likely hours or days). Despite the apparent magnitude of the problem, desktop software can be employed to systematically search for and find optimum solutions, often within just several minutes.

Each of the individual objectives could be optimized individually and the resulting lists of optimum investments could be compared to identify areas of commonality. Alternatively, the objectives could be combined using any of several widely employed multi-objective optimization techniques, such as the constraint method, weighted objective functions, goal programming, and adaptive searches, among others (Cohon and Marks 1975). In either case, the output would be a recommended list of specific abatement and restoration investments that would most effectively address the stated objectives.

7.3 Plan for Optimizing Merrimack River Watershed Investments

The plan for optimizing abatement and restoration alternatives for the Merrimack River Watershed is a two-phased program. Phase I, which is currently funded, will yield a list of decision variables and objectives, and through collaborative preparation, will help educate project sponsors and other stakeholders about the process of mathematical optimization, the tools, their limitations, and ultimately, what can be expected as a deliverable. Phase II, which is not yet funded, will fine-tune the sensitivity analysis from Phase I with specific cost:benefit analysis for each specific investment, thereby formulating many of the constraints and mathematical contributions to the objective functions.

Phase I:

- Identify the decision variables, which will be specific alternatives for abatement, restoration, and water management (Task 13)

- Identify spatially distributed sensitivities that can be used in Phase II to associate specific projects with specific benefits (Task 12 – the generalized pollution reduction scenarios will yield spatially-distributed results)

- Sponsor a workshop with project participants and interested parties to illustrate how multi-objective optimization can be an effective, collaborative process, and can even occur *during* public meetings. Examples of multi-objective optimization programs will be demonstrated so that participants can see first hand how this type of tool can effectively lead multiple parties toward consensus and bring the planning process to closure. In addition to serving as an educational forum, another central focus of the workshop will be to identify the objectives for the subsequent optimization program, and to achieve consensus on a group of objectives that all parties deem worthy of consideration.

Phase II:

- Develop detailed cost:benefit relationships for each alternative identified in Task 13 of Phase I (both potential environmental and economic benefits shall be assessed). Planners Collaborative, Inc. and Industrial Economics, Inc., economic and planning firms, have been included in the CDM Project Team to help conduct this process using understandable and defensible methods.

- Formulate optimization program to select the investments that best satisfy the objectives

- Sponsor a workshop with project participants and interested parties to demonstrate how the program works and to run the program under alternative objectives. Results can be reviewed and compared in a collaborative setting.

CDM will analyze the results of the optimization runs and other output from the workshop, and recommend a prioritized list of investments for a multi-objective watershed management plan for the Merrimack River watershed.

Section 8
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Appendix A

November 8, 2000 Modeling Workshop Presentation

CDM

Merrimack River Watershed Assessment Study:

Modeling Workshop

Gary Mercer, P.E.
Kirk Westphal
Beth Rudolph

November 8, 2002

Sponsor Communities:
Manchester, NH
Nashua, NH
Lowell, MA
GLSD, MA
Haverhill, MA

US Army Corps of Engineers

Merrimack River Watershed Council

Presentation Overview

- Overview of Project – Gary Mercer
- Modeling Objectives and Strategies – Kirk Westphal
- Complementary Sampling Plan – Beth Rudolph
- Break
- Open Discussion
  - Modeling objectives/strategy
  - Data requirements
  - Uncertainty issues
  - Others
- Workshop Questionnaire

Workshop Objectives

- Present an overview of the study
- Present objectives and strategies for the modeling effort
- Review the proposed monitoring program from a modeling perspective
- Have an open discussion of technical and non-technical issues
- Solicit responses to fundamental questions about the overall modeling effort
- Achieve consensus for modeling strategy and objectives

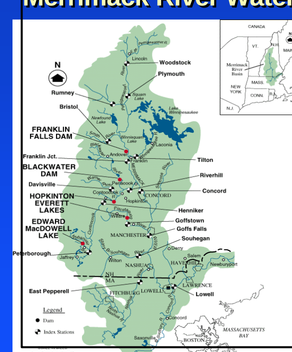
Project Background

- Five communities on the Merrimack River currently developing/ implementing long-term CSO control plans
  - Collective cost of up to one-billion dollars over next 20-years
- Concerned over adequate understanding of
  - Existing conditions,
  - Pollution sources and effects,
  - Potential basin-wide benefits of CSO abatement and restoration projects

Project Overview

- Purpose:
  - Develop a watershed management plan to guide investments in the basin aimed at achieving conditions that support beneficial uses
- Project Phasing:
  - Phase I: Existing conditions review, sampling and modeling effort, initial evaluation of pollution abatement strategies & restoration projects
  - Phase II: Additional monitoring and more detailed analysis of proposed projects

Merrimack River Watershed



- 5010 sq. mi. basin in NH (76%) and MA (24%)
- Designated Uses:
  - Water Supply
  - Aquatic Habitat
  - Recreation
  - Hydropower
- Significant economic and natural resource in New England
- Largest perceived challenges to WQ: CSO discharges and urban runoff

Cost-Sharing Structure

- US Army Corps of Engineers
  - Financial and technical assistance
- Community Partnership- “CSO Coalition”
  - Haverhill, MA
  - Lowell, MA
  - Greater Lawrence Sanitary District (GLSD)
  - Manchester, NH
  - Nashua, NH
- Merrimack River Watershed Council (MRWC)

Study Objectives

- Characterize the effects of pollutants in the River with respect to WQ standards and designated uses.
- Determine the relative contribution of pollutants from major tributaries and other sources, including:
  - CSOs, municipal WWTPs, stormwater runoff, septic systems, etc.
- Determine dry/ wet-weather and seasonal differences in water quality.

Objectives (continued)

- Identify mainstem Merrimack River segments exceeding WQ standards.
- Simulate the effects of various investments with respect to designated uses.

Abatement
Restoration
Control

→

Uses:
Water Supply
Aquatic Habitat & Fishing
Recreation
Hydropower

- Perform planning-level cost & benefit analysis of various alternatives.

General Plan:

METHODS:
Data Review
Field Work
Modeling
Data Mgt.

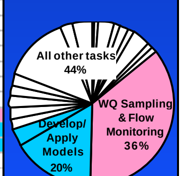
→

Answers to Fundamental Questions:

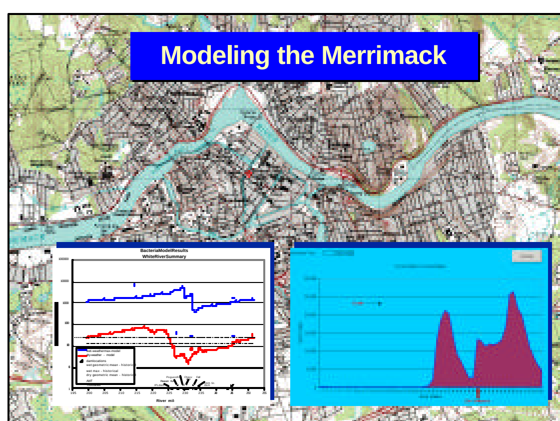
1. What/where are the beneficial uses?
2. What are the relative contributions of pollution by type, source, and area?
3. What are the effects of pollution in the river?
4. How does pollution affect uses?
5. How sensitive is use attainment to various investment strategies?
6. What is the best investment plan to support uses?

Overview of Phase I Tasks

Task No.	Task Description	Estimated Budget
1	Evaluation of Existing Conditions	$13,000
2	Inventory of Current & Potential Uses	$12,000
3	Information on Source of Pollutants	$61,000
4	Develop Modeling Methodology	$30,000
5	Data Management Program	$23,000
6	Develop Screening Level Model	$28,000
7	Hydrology/ Hydraulics Data	$72,000
8	Design WQ Sampling Program	$22,000
9	Quality Assurance Project Plan (QAPP)	$18,000
10	WQ Sampling & Flow Monitoring	$700,000
11	Develop WQ Models	$320,000
12	River Analysis using Developed Models	$68,000
13	Plan Formulation	$28,000
14	Alternatives Analysis	$50,000
15	Inventory Ecosystem Restoration Opps.	$44,000
16	Geographic Information System (GIS)	$45,000
17	Public Involvement/ Outreach (MRWC)	$50,000
18	Project Management (Corps+ MRWC)	$241,000
19	Report Preparation	$50,000
20	Corps Independent Technical Review	$75,000



Modeling the Merrimack



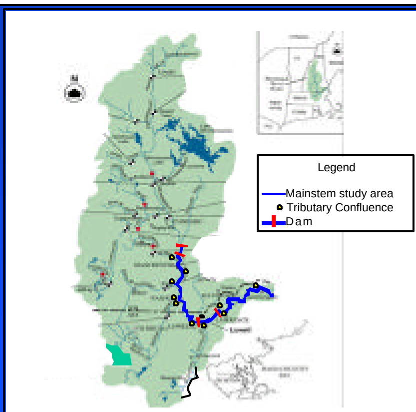
Modeling Plan Overview

Program Phase	Modeling Tools	Intended Uses
Phase I	Screening Model	Estimate relative pollutant loads
Phase I	Simulation Models	Estimate sensitivity to load reductions
Phase II	Screening/ Optimization Models	Identify prioritized investment plan

Overview of Modeling Program

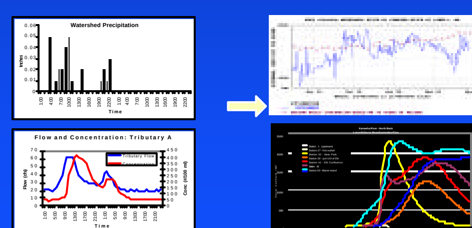
- Models will be developed for
  - Watershed pollutant loading
  - Watershed hydrology
  - Hydraulic routing in channels
  - Receiving water quality
- Models will be calibrated to results of WQ and flow monitoring program
- Modeling will be used to investigate potential effectiveness of various investment plans for abatement and control
- Modeling results will be compared with state WQ standards and designated water uses.
- We will simulate bacteria, nutrients, metals, and DO

Study Area



Modeling Objectives

- Simulate loading, transport, and water quality with reasonable confidence
- Simulate the dynamic nature of storm events and their effects on the river



Modeling Objective (continued)

- Simulate lowflow/baseflow conditions
- Simulate the sensitivity of the receiving water to incremental reductions in various pollutant loads:
  - CSOs
  - WWTPs
  - Urban stormwater
  - Non-point source
- Simulate sensitivity of WQ to dams and operating rules

Utility of Models

- Questions that models CAN answer:
  - What is likely to happen if pollutant loads change?
  - How sensitive does the river system appear to be to changes in specific inputs?
  - How will WQ and designated uses likely improve?
  - How confident can we be in the results?
  - What investment plans offer the greatest benefits?
- Questions the models CANNOT answer:
  - What will be the future loading conditions?
  - What will be the future flow conditions?
  - What will actually happen as a result of investments?
  - What are the optimal investments?

Model Development Task Deliverables :

- Task 4: **Develop Modeling Methodology** (in progress)
  - Tech Memo: Model selection, data requirements, interface strategy, boundary conditions, tributary requirements
- Task 6: **Screening Level Model** (authorized)
  - Report: Identify likely relative contributions of pollution, Identify focus areas for detailed numerical models (geographic areas, pollutants, etc.)
- Task 11: **Develop Water Quality Models**
  - Report: Model Development and Calibration – to include rainfall-runoff model(s), watershed loading model(s), river hydraulics models(s), receiving water quality model(s), linkage strategy

Modeling/Analysis Task Deliverables:

- Task 12: **River Analysis Using Models**
  - Report: Incremental *Receiving Water Sensitivity* to CSO reductions, stormdrain abatement, NPS reduction, WWTP reductions, Dam removal, Alternate hydropower operations (specific controls considered in Task 14).
- Task 13: **Plan Formulation**
  - Tech Memo: Summary of suggested abatement/control measures to be analyzed in Task 14
- Task 14: **Alternatives Analysis**
  - Results will be included in Final Report
  - Estimate pollution reduction levels for each alternative from Task 13
  - ID water quality benefit for each measure from Task 13 using sensitivities:
    - *Alternative A → 15% Reductions in CSO volume → 20% improvement in use attainment*
  - Planning Level Economic Analysis

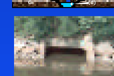
Software Selection Guidelines

- **Continuous and event-based dynamic simulation (flow and WQ)**
- **Resolution in minutes**
- **Emphasis on urban hydrology and pollutant loads**
- **Non-point source load simulation**
- **Fate/Transport of bacteria, nutrients, metals, DO, BOD**
- **Compatibility**
  - **Must interface easily with external CSO models**
  - **Loading, transport, receiving WQ must interface effectively**
- **Understandable output**

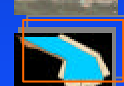
Recommended Models:

Watershed NPS Loads → **EPA SWMM Runoff Block**

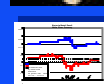
Watershed Rainfall-Runoff → **EPA SWMM Runoff Block**



CSO Systems → **EPA SWMM Runoff/Extran Blocks**



Channel Routing → **EPA SWMM EXTRAN Block**

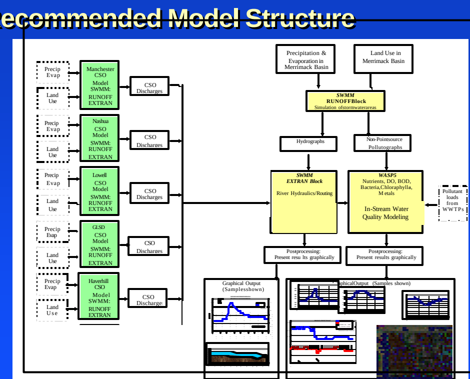


Receiving Water Quality → **EPA WASP**

Basis of Recommendation

- **Models are Flexible and Comprehensive:**
  - **Scenarios, constituents**
- **Models are Manageable:**
  - **Interface with existing SWMM CSO Models**
  - **SWMM and WASP are easily linked**
  - **Less data intensive than others (HSPF)**
  - **Graphical post-processors (GIS, MikeSWMM, WASP…)**
- **Models are Targeted at urban stormwater**
- **Public Domain**
- **Widely applied and accepted by regulatory agencies**

Recommended Model Structure



Model Development Process

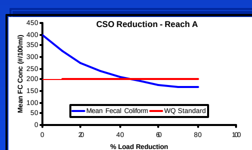
- Update existing CSO SWMM models as necessary
- Develop SWMM and WASP models of watershed and river
- Develop calibration/validation plan
- Calibrate runoff and routing model elements to USGS records and other flow monitoring data
- Calibrate loading and receiving water quality model elements to sampling data
- Validate each model component

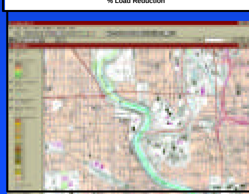
Model Application

- Simulate current conditions (WQ and uses)
- Simulate future conditions (WQ and uses)
- Sensitivity Analysis
  - Incremental CSO reductions
  - Incremental WWTP reductions
  - Incremental urban stormwater reductions
  - Incremental NPS reductions
  - Product: Sensitivity Matrix / Curves
- Refined analysis as needed for specific investments

What we'll do with the results

- Generate sensitivity curves for each impaired reach
- Compare with WQ standards/uses
- Translate into graphical and tabular formats
- Assess Uncertainty
- Apply sensitivity matrix to evaluate benefits associated with various investment plans





Sampling Plan Primary Objectives:

- Measure & assess relative contributions from pollution sources (point and non-point)
- Measure effects of pollutants in mainstem
- Identify reaches that do not meet WQ standards
  - Geographic extent
  - Seasonal & climatological (dry vs wet) dependence
  - Duration (wet only)
- Assess biological health of ecosystem
- Understand general mixing patterns
- Provide data for model calibration

Sampling Plan Overview

- Sampling Season: April- November 2003
- Four dry-weather events:
  - Spring (April & May) - 1 event
  - Summer (June through mid-Sept)- 2 events
  - Fall (mid- September through November): 1 event
- Three wet-weather events:
  - Likely in Spring and Fall
- Sampling performed on 80-mile reach from Hooksett Dam to Atlantic Ocean
- WQ sampling focus on bacteria, nutrients, & metals (based on 303(d) lists)

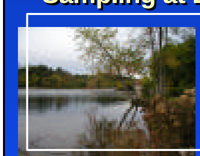
Proposed WQ Parameters

Indicator Organisms	Nutrients & Impacts	Oxygen & Oxygen Demand	Metals	Field Measurements
•E. Coli •Fecal Coliform •Enterococcus (marine waters only)	•Total Phosphorus •Ammonia- N •Nitrate/ Nitrite •Total Kjeldahl Nitrogen (TKN) •Chlorophyll-a	•Dissolved Oxygen (DO)- (Winkler titration) •BOD_5 •BOD_{20} (Dry-weather only)	•Cadmium •Copper •Lead •Iron •Nickel •Zinc •Hardness	•*In situ* Temperature, DO, pH, & Conductivity •Vertical Temp/ DO profiles (U/S of dams only) •Diurnal DO sweeps (dry-weather only) •Secchi Disk Depth •Streamflow (select stations only)

Proposed Sampling Stations

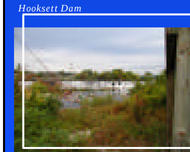
WQ Station	Dry- weather	Wet -weather
Source Sampling:		
--Mouth of 11 major tributaries	X	X
--5 CSO outfall pipes		X
--10 stormdrain outfalls		X
Instream Response:		
--D/S of 11 WWTPs	X	X
--U/S & D/S of 5 CSO communities	X	X
--D/S of 10 stormdrain outfalls		X
--2 Shellfishing beds	X	X
--Public Beach & Boat Launch	X	X
Sampling at Dams:		
--U/S of 4 dams		X
--D/S of 4 dams	X	X

Sampling at Dams

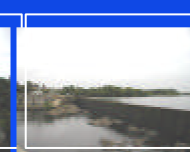

Hooksett Dam

4 dams along the mainstem:

- Hooksett Dam (Hooksett, NH)
- Amoskeag Dam (Manchester, NH)
- Pawtucket Dam (Lowell, MA)
- Essex Dam (Lawrence, MA)


Amoskeag Dam


Pawtucket Dam


Essex Dam