1. INTRODUCTION

This report describes the development, calibration/confirmation, and application of a linked hydrodynamic-sediment transport-water quality model for the Upper Mississippi River from Lock and Dam No. 1 through Lock and Dam No. 4 below Lake Pepin. The model, called the Upper Mississippi River - Lake Pepin Water Quality Model (UMR-LP model) was developed as a tool to support a combined TMDL study for turbidity and nutrient enrichment.

1.1 BACKGROUND AND PROJECT OBJECTIVES

Lake Pepin is a natural impoundment in Pool 4 of the Upper Mississippi River. The Lake Pepin watershed is very large (approximately 48,630 square miles) and spans several EPA-defined ecoregions. Multiple water body segments in the Lake Pepin watershed are included on Minnesota's current 303(d) list of impaired waters. The Clean Water Act requires that Total Maximum Daily Loads (TMDLs) be developed for these impaired waters. Waste Load Allocations and Load Allocations will be established through the TMDL process for the following watersheds: Minnesota River Basin to Jordan, the Upper Mississippi River Basin upstream of Anoka, the St. Croix River Basin to Stillwater, the Twin Cities Metropolitan Area, and some smaller tributaries. Figure 1-1 provides an overview of the study area, showing key features and monitoring station locations.

This report describes a project that contributes to the multi-phase Lake Pepin Watershed TMDL program. The long-term goal of the Lake Pepin TMDL is to protect and restore beneficial uses of the Mississippi River from the confluence with the Minnesota River through Lake Pepin by attaining appropriate nutrient and turbidity levels. This project was designed to meet the following specific objectives:

- Gain an improved understanding of eutrophication and turbidity impairments in the study area;
- Determine if additional data are needed to complete the TMDL analysis;
- Develop and calibrate a modeling framework that simulates the response of the lake to reduced nutrient and sediment loads;
- Develop and apply a user-friendly tool for allocating nutrient and sediment loads; and
- Interact with other contributors to the overall Lake Pepin watershed TMDL program to assist the State of Minnesota in completing the TMDL for this system.

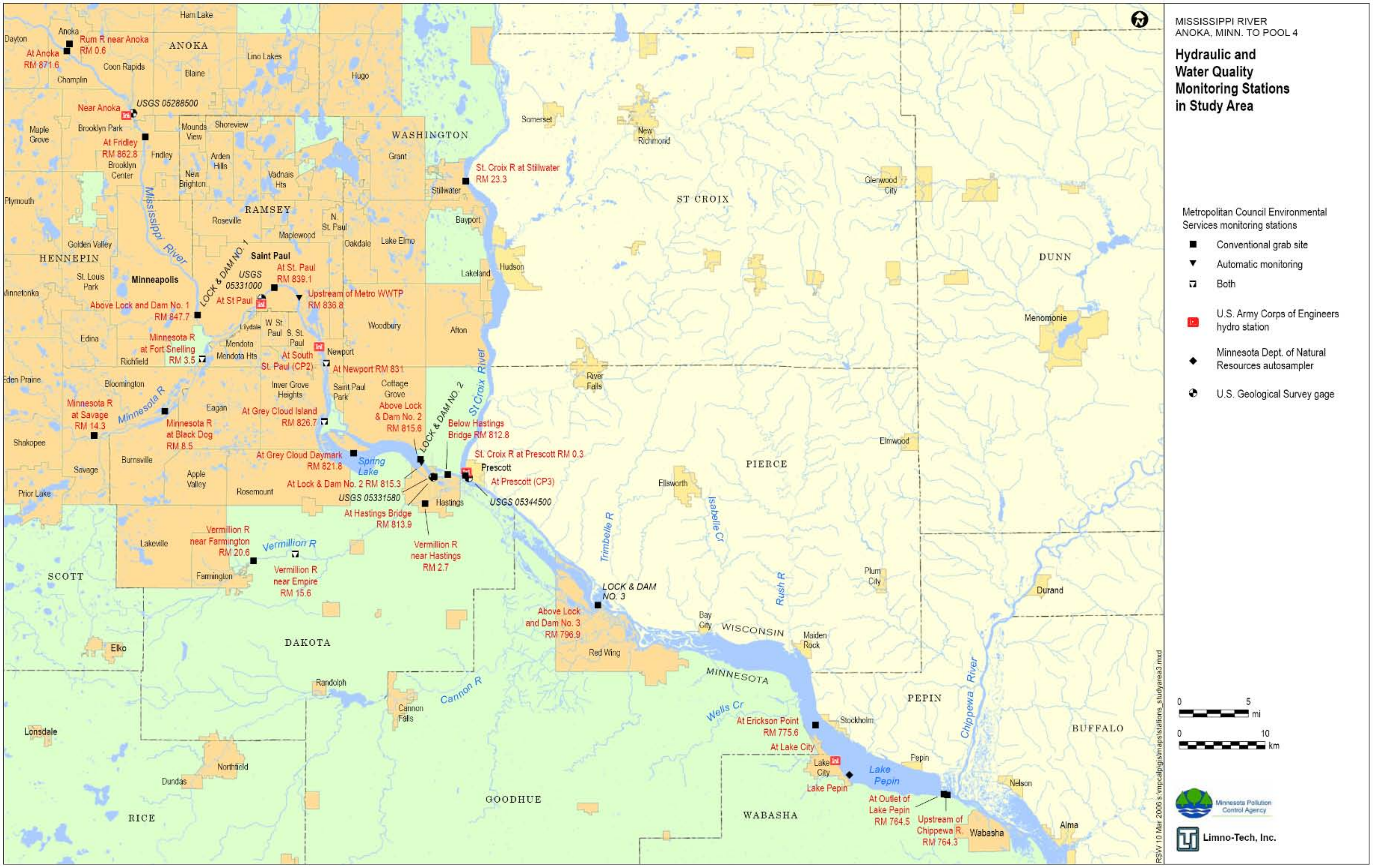

Figure 1-1. Study Area Map

1.2 PROBLEM SPECIFICATION

Explicit specification of the problem to be addressed (i.e., detailed statement of management questions) is a critical element of any modeling project. Planning the project with the end in mind assures the development of the most appropriate conceptual model and the most appropriate model complexity. It must, therefore, include a clear and complete statement of policy, management, and/or scientific objectives, model spatial and temporal domain and resolution characteristics, as well as program constraints (e.g., legal, institutional, data, time and economics). Some considerations for each aspect include:

- **Management objectives** are statements of what questions a model has to answer. The statement of modeling objectives should include: the water quality state variables of concern; the stressors (model inputs) driving those state variables and their control options; the TMDL water quality targets including appropriate time and space scales at which to assess attainment; decision maker acceptance; and, very importantly, the desired accuracy of the model.

- Specifying the **model domain characteristics** includes: identification of the environmental domain being modeled; specification of transport and transformation processes within that domain that are relevant to the policy/management/research objectives; specification of important time and space scales inherent in transport and transformation processes within that domain in comparison with the time and space scales of the problem objectives; and any peculiar conditions of the domain that will affect model selection or new model construction.

- Problem specification should include a discussion of the potential **programmatic constraints**. These address: time and budget; available data or resources to acquire more data; legal and institutional considerations; computer resource constraints; and experience and expertise of the modeling staff.

1.2.1 Management Objectives

The primary project objective is to develop a model that can support a TMDL for turbidity and nutrient-chlorophyll *a* impairments in Pools 2, 3, and 4 of the Upper Mississippi River. In a TMDL study, the primary management objectives are the establishment of water quality targets for the pollutants of concern, and the allocation of pollutant loads to meet those targets. The Upper Mississippi River – Lake Pepin system is listed on the 2006 Minnesota 303(d) priority water body list for turbidity in Pools 2 and 3 and for nutrients in Spring Lake and Lake Pepin. MPCA recently decided to remove Spring Lake from the 303(d) list for nutrient impairment (MPCA, 2008a), so explicit targets for chlorophyll a and phosphorus concentrations will no longer be applied to Spring Lake (pending final EPA acceptance of the 2010 impaired

waters list in Spring 2010). The targets listed below are provisional targets at this time. They are subject to change as the MPCA develops site-specific standards for eutrophication and submerged aquatic vegetation, with input from the Science Advisory Panel and Stakeholder Advisory Committee, subject to EPA approval.

The MPCA lists a water body for turbidity if it exceeds 25 NTU in more than 10% of the monitoring samples. Therefore, the preliminary turbidity target applied in the modeling analyses was 25 NTU in less than 10% of the monitoring samples for flows up to the 90^{th} percentile (i.e., up to 31,400 cfs at St. Paul). A site-specific criterion of a long-term median summer (June-September) average of 32 mg/L TSS has been proposed to support the promotion of submerged aquatic vegetation (SAV) from Pool 2 to Upper Lake Pepin (Sullivan et al., 2009).

In Minnesota, nutrient-impaired water bodies are listed based on a narrative standard and the use of EPA ecoregion-based threshold values for TP, chlorophyll *a*, and Secchi depth based on state guidance. However, a new rule allows waterbody-specific criteria to be developed and used for lakes and reservoirs like Spring Lake and Lake Pepin. For Lake Pepin, the whole lake summer mean viable chlorophyll *a* criterion is proposed as less than 32 μg/L. An analysis of UMR-LP model results to quantify the phosphorus load necessary to achieve these chlorophyll targets, along with analyses of available data, have been used to develop a proposed criterion for total phosphorus (TP) of 0.100 mg/L. For Secchi depth, a target of 0.8 meter is being considered (MPCA, 2008b; Wasley and Heiskary, 2009).

In addition to specifying the temporal and spatial aggregation for the TMDL targets as specified above, it is important to specify the critical conditions under which the targets must be met. For the nutrient targets, critical conditions will likely be low-flow conditions when the hydraulic residence time in Lake Pepin provides enough residence time in the system for phytoplankton blooms to develop, given sufficient temperature, light, and nutrients. On the other hand, the critical conditions for turbidity are likely to be high-flow conditions in the spring. This reality requires assessing the system under a range of flow conditions and potentially under a range of spring high-flow and summer low-flow combinations.

Finally, a very important consideration for establishing the required model sophistication is the specification of the precision and accuracy of the load – response relationship used to set the phosphorus TMDL. The uncertainty of the model calibration and confirmation comparison with data has been assessed in this regard, and a margin of safety for the TMDL can be established based on this analysis.

There are other management concerns in addition to the TMDL targets that the model may support. Among these are:

- Restoration of emergent and submerged aquatic vegetation (SAV) in the system to levels observed during low flow periods with low turbidity such as in the 1980s and early 1990s. Therefore, stakeholders are interested in the

potential for SAV growth as the TMDL targets are met, especially in Pool 2 and upper Pool 4 above Lake Pepin.

- The potential for occurrence of blue-green algal blooms in the system. Therefore, the model should have the capability to simulate the succession of phytoplankton functional groups through the growing season on the basis of light, temperature, nutrient and zooplankton grazing conditions.

- The sedimentation rate in Lake Pepin as a function of upstream turbidity (solids load).

- Finally, assessment of the nitrogen export from the system to the Mississippi River below Lake Pepin, because of a concern about impacts on downstream reaches of the Mississippi River, and the contribution to the hypoxia-causing nitrogen load to the Gulf of Mexico.

These project management objectives require a relatively sophisticated model that is capable of assessing both turbidity and nutrient enrichment impacts in this system. For this reason, a fine-scale hydrodynamic and sediment transport model linked to an advanced eutrophication and solids dynamics water quality model was selected. This model framework can quantify the relationship between the endpoints of concern and natural and anthropogenic loads and environmental conditions of importance.

1.2.2 System Characteristics

The complex nature of the Upper Mississippi River – Lake Pepin system, in addition to the complex management issues presented above, require a model that is not only complex in terms of process resolution but is complex in terms of spatial and temporal resolution. The system stretches for approximately 90 miles and consists of three morphometrically and hydraulically distinct pools, separated by lock and dam control structures. There is considerable variability both laterally and longitudinally of the system bathymetry, including channels, shoals, deltas, and impoundments. There are several islands throughout the system that complicate the hydraulics. The flow distribution at the head of Lake Pepin is complex, and its distribution in conjunction with the relative temperature difference between the upstream flow and Lake Pepin can impact vertical temperature stratification and the upper mixed layer depth in the water column. Also, the depth of the upper mixed layer relative to light penetration in Lake Pepin has a significant impact on phytoplankton chlorophyll *a* concentrations.

1.2.3 Programmatic Constraints

The time and available resources for conducting this TMDL model development project at the desired high level of complexity represent a definite challenge; however, the available data for this system are sufficient to support the level of complexity being employed. There are a few additional data/research activities that were recommended early in this project to better constrain some aspects of the model

framework. Another benefit that helps to alleviate the programmatic challenges is the significant amount of previous research and synthesis modeling work that have been conducted on this system. The project benefited greatly from this previous work; it has allowed the model of the system to evolve and become more able to address the sophisticated management questions being posed.

In addition to time and budget considerations, an additional programmatic requirement is that the model be publicly available and usable by the MPCA staff when completed. This requires thorough documentation of the model framework and model applications conducted. It also requires a training process to assist MPCA in understanding the model and in utilizing it beyond the applications conducted within this project. The model must also be scientifically peer reviewed by a Science Advisory Panel and by MPCA technical staff. These considerations were important factors in the model selection process described in Chapter 2 of this report.

1.3 PROJECT APPROACH

The problem specification outcomes described in Section 1.2 provided the basis for development of the project approach. Furthermore, the overall project approach followed EPA's Draft Guidance on the Development, Evaluation, and Application of Regulatory Environmental Models (EPA 2003) because the model will be used for regulatory purposes to support a combined TMDL study for turbidity and nutrient enrichment. In addition to this EPA guidance, the project approach was based on guiding principles developed for modeling within the TMDL process (DePinto, et al., 2004).

Based on the above guidance, the general approach to model development and application used for this project adhered to the following steps in the regulatory environmental modeling process: 1) problem specification; 2) model framework selection and formulation; 3) model development; 4) model evaluation; and 5) model application. These steps were approached sequentially, but allowed for reiteration of a previous step when information gained necessitated it. There is also an ongoing bidirectional interaction between the model and system data throughout this process. The entire modeling process, including its interaction with data and iterative nature, is depicted in Figure 1-2.

An important overarching component of this project was the adherence to an open modeling process throughout the project that involved continual interaction with all stakeholders at each step in the process (through the Stakeholder Advisory Committee (SAC)); and ongoing model review by stakeholder, agency staff, and peers (through the Science Advisory Panel (SAP)).

For the Upper Mississippi River – Lake Pepin Water Quality Modeling Project, the specific modeling steps were as follows:

1. **Specify the problem**: Identify management objectives, system characteristics, and programmatic constraints.

2. **Select the model framework**: Develop conceptual model, evaluate options and select framework that will best address factors identified in problem specification phase.
3. **Build model framework**: Encode the model framework, configure the model framework to the system and compare with the previous model developed by HydroQual, and conduct preliminary diagnostic and sensitivity analyses to assess the behavior of the system and the ability of the model to meet the problem specification.
4. **Develop system-specific model application:** Revise the model framework as necessitated by above analysis and calibrate the revised model.
5. **Evaluate the model**: Conduct model verification to assure coding accuracy, confirm model with a different data set, and conduct model diagnostic/sensitivity/uncertainty analyses.
6. **Apply the model**: Evaluate the ability of source reductions to achieve the goals of the TMDL.

A considerable amount of data collection and system analysis was already completed on this system before this project was initiated (MCES, 2002). The project approach was designed to use all existing information to the greatest extent possible, provided it was high quality data and analysis and consistent with the objectives of this approach.

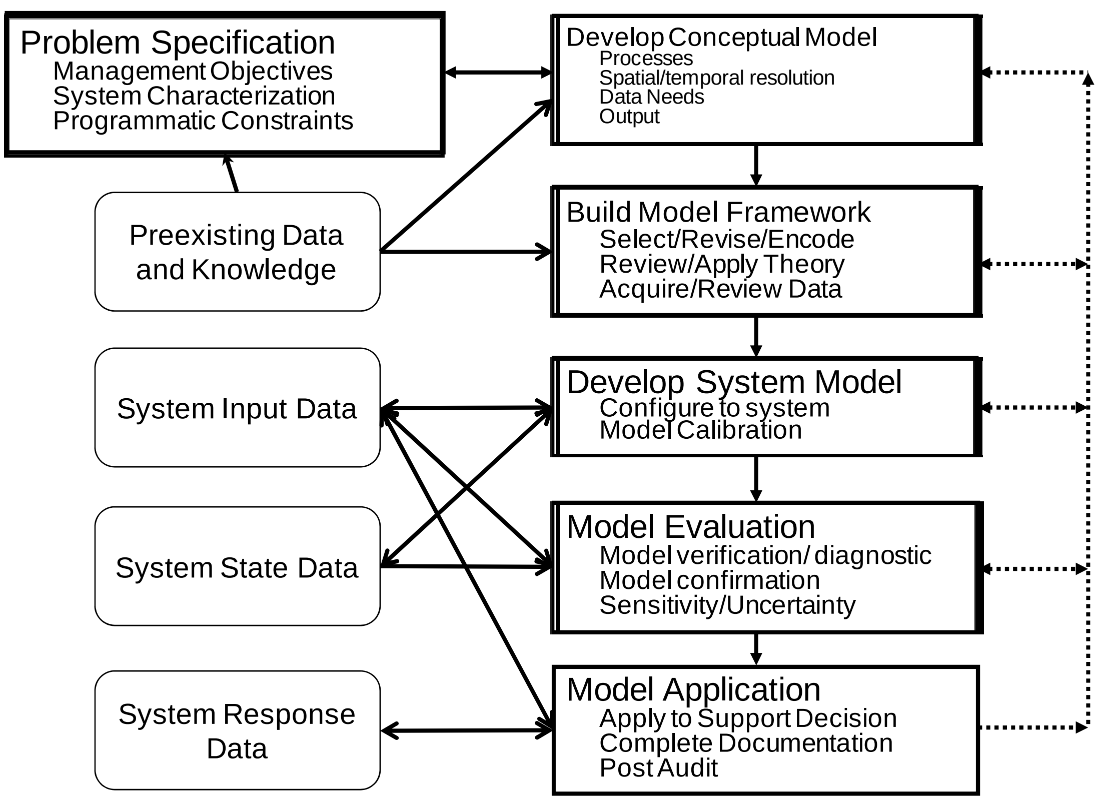

Figure 1-2. Model development process showing interaction with system data and theory and showing potential iteration of steps along the process.

1.3.1 Problem Specification

Completing the problem specification phase involved a thorough review of the previous studies on the system and of the available data for the system. Also, the MPCA had previously identified a fairly thorough description of the problems being addressed for this system. A key component of problem specification was the participation of project team members in two goal setting, or problem specification, workshops. The workshops were held in St. Paul on January 23 and May 3, 2006. Workshop participants included technical experts and decision makers from the MPCA, and academic and government scientists serving on the Science Advisory Panel (SAP). The primary purpose of the workshops was to discuss and reach a consensus on the three major aspects of problem specification: management objectives; system characteristics; and program constraints. This was an important component of the project because the workshop outcomes govern the model selection process, model formulation, selection of calibration metrics and evaluation criteria, and the model application approach.

1.3.2 Model Framework Selection

The model selection process began with an examination of the advanced eutrophication model developed by HydroQual, Inc. (HQI) for the Lake Pepin Phosphorus Study (HydroQual 2002b; HydroQual 2002c). The model has been referred to as the HQI UMR (Upper Mississippi River) model. Some concerns related to the code were raised, and the project team then investigated the feasibility of using an alternative approach. The outcome was a recommendation that the existing UMR models be ported to the public domain versions of ECOMSED and RCA, with some modifications. Details on the model selection process are provided in Chapter 2.

1.3.3 Model Development

The first step in building the model framework was to develop a conceptual model. To accomplish this, the physical, chemical, and biological processes of importance and data needs were identified, as well as model output required to meet the problem specification. The UMR-LP model was encoded and configured to the system. The UMR-LP model was then compared to the HQI UMR model to demonstrate that similar results were achieved.

LTI also conducted preliminary diagnostic and sensitivity analyses as part of model framework development. The purpose of these analyses was to support goal setting, identify process and data gaps in the model, and to provide insights for recalibration. For diagnostics of model response to the various pollutant sources or loads, the approach employed was to shut off individual load categories of non-volatile suspended solids (NVSS) and phosphorus and run the model for the same three years to assess the system’s response for key output variables. Mass balance process component analyses were also conducted. The results of these preliminary analyses were presented and discussed in the LTI Year 1 report (LimnoTech, 2006). Based on these analyses and discussions with the SAP and SAC, the UMR-LP model was

revised. Chapter 2 provides details on the model development process. Additional diagnostic analyses are presented in Section 5 of this report.

1.3.4 Model Calibration and Confirmation/Evaluation

The first step in the model calibration was to configure the model to the system being investigated and to compile all necessary model input data, including loads, flows, boundary conditions, hydro-meteorological inputs, and initial conditions. Details on this process are presented in Chapter 3.

Once the model was configured to the system, it was calibrated against field data in order to develop a set of model coefficients that were both consistent with theory and provided the best overall fit to the spatial and temporal profiles of all model state variables. Monitoring data for the system from 1985 – 2006, including the MCES low-flow monitoring data, were used for calibration and confirmation of the calibrated model. Again, details on the source and organization of the data used for model calibration and confirmation are presented in Chapter 3. A decision was made to use half of the monitored years (1996 – 2006) for model calibration, and the earlier years (1985 – 1995) for model confirmation. It should be noted that the calibration period included the intense low-flow monitoring program conducted in 2006 (10^{th} percentile summer (June – September) flow at Prescott) and the 86^{th} percentile annual flow at Prescott in 2002. The earlier confirmation period included the one percent summer flow in 1988 and the highest annual flow on record in 1993. It was important to test the model's ability to simulate the system response over the full range of flow conditions, because high flows represent the critical conditions for turbidity, while low flows represent the critical conditions for nutrient-stimulated phytoplankton growth.

The calibration process began by running the model for the calibration period with initial parameterization based on theory and the previous coefficients employed by HQI in its HQI UMR model development. Calibration of a model of this complexity to a 10-year data set is an extremely difficult and time consuming process. The reason, of course, is that the model has many state variables and even more processes describing the interactions among those state variables. Also, virtually all deterministic, process-oriented water quality models have many more coefficients than state variables, meaning that there is not a unique set of coefficients that may lead to a satisfactory calibration.

As indicated in Figure 1-2, the model calibration is often an iterative process, which depends on the results of model evaluation and preliminary application relative to expectations and error tolerance. Indeed, this model was recalibrated twice subsequent to the provisional calibration presented in the June, 2007 report (LimnoTech 2007). A discussion of the rationale for our two model re-calibration efforts during the past year is presented in Chapter 5.

The approach to model confirmation consisted of a suite of evaluation techniques, including those recommended in the EPA Draft Regulatory Environmental Modeling

Guidance (EPA 2003) and in the literature (Ramaswami, et al., 2005; Beck, et al., 2000). Since all models are actually simplifications of the real world and since all water quality models are not completely mechanistic, no model can ever be truly validated (Oreskes et al. 1994). In fact, most modelers prefer to use the term “confirmation” or “corroboration” rather than “validation” for their model evaluation process.

Model performance criteria for the evaluation process were based on the desired use and level of accuracy of the model projections. Techniques used in model evaluation included: model code verification, model performance evaluation by confirmation against an independent data set relative to the data used for calibration (1985 – 1995 data in this case), and application of selected sensitivity analysis and uncertainty analysis diagnostics. The UMR-LP model calibration/confirmation and diagnostic analyses for the hydrodynamic and NVSS modeling and the water quality modeling are described in Chapters 4 and 5, respectively.

A model user-friendly interface (WinModel) was developed to assist the calibration and confirmation process. This tool consists of a large database of system monitoring data and model input and output parameters. The data base can be manipulated to present model – data comparisons in a variety of ways. The final result of the iterative calibration/confirmation process is a UMR-LP model that LTI believes is robust and responsive to large changes in nutrients and solids loads, such as those being evaluated in this TMDL.

1.3.5 Model Application

Application of the calibrated and confirmed model to the project management questions was conducted in an open environment that allowed for close interaction of all stakeholders, including the SAP and the SAC. A full range of source category and basin-specific load (phosphorus and suspended solids) reduction scenarios was run in order to produce “load – response” relationships for appropriate water quality targets. To assist all managers and stakeholders in reviewing the results of the UMR-LP model application, a customized spreadsheet tool called the Management Analysis Tool (MAT) was developed to permit visualization and analysis of the full suite of management scenarios across scenarios, metrics, locations, and years in a variety of ways. The MAT allows rapid and efficient comparison of load reduction scenarios, and evaluation of results relative to TMDL targets. A description of the MAT and a presentation of its use to explore the results of the model application conducted to date are presented in Chapter 6.