Lower Vermillion River Watershed Turbidity TMDL

Phase III Report: TMDL Development

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Submitted to:
United States Environmental Protection Agency

Submitted by:
Minnesota Pollution Control Agency & Tetra Tech

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TMDL Summary

EPA/MPCA Required Elements	Summary	TMDL Page #
Location	The Lower Vermillion River is located in Dakota and Goodhue Counties in southeastern Minnesota. It is part of the Lower Mississippi River Basin.	10
303(d) Listing Information	▪ Lower Vermillion River: River ID# 07040001-504 ▪ Impaired Beneficial Use: Aquatic Life ▪ Impairment/TMDL Pollutant(s) of Concern: Turbidity ▪ Priority ranking of the waterbody: Scheduled for TMDL Completion in 2008 ▪ Original listing year: 1994	9
Applicable Water Quality Standards/ Numeric Targets	The chronic turbidity standard for Class 2B waters is 25 NTU [Minnesota Administrative Rules. 7050.0220. Subpart. 4a].	9
Loading Capacity (expressed as daily load)	The loading capacity for the Lower Vermillion River is defined for two conditions: Mode 0 (Minimal Pool 3 Inflow): 7,793 kg/day TSS Mode 1 (Significant Pool 3 Inflow): 70,321 kg/ day TSS	30-31

EPA/MPCA Required Elements	Source	Permit #	Individual WLA (kg/day)		TMDL Page #
			Mode 0	Mode 1	
Wasteload Allocation	Elko/New Market WWTP	MN0056219	125	125	32-35
	Intek Plastics Inc	MN0003417	14.4	14.4	
	Vermillion WWTP	MN0025101	9.2	9.2	
	Apple Valley (MS4)	MS400074	75	464	
	Burnsville (MS4)	MS400076	11	68	
	Lakeville (MS4)	MS400099	363	2,250	
	Farmington (MS4)	MS400090	94	582	
	Rosemount (MS4)	MS400117	26	164	
	Empire Township (MS4)	MS400135	279	1,730	
	Hastings (MS4)	MS400240	64	396	
	MnDOT Metro (MS4)	MS400170	Wasteload allocations for MNDOT and county roads are included in respective wasteload allocations for the municipalities that contain them.		
	Dakota County (MS4)	MS400132			
	Scott County (MS4)	MS400154			
	Reserve Capacity	NA			

EPA/MPCA Required Elements	Source	LA (kg/day)		TMDL Page #
		Mode 0	Mode 1	
Load Allocation	Upper Vermillion River	1,478	9,383	35
	Mississippi River Pool 3	1	45,081	
	Mississippi River Pool 4	1	1	
	Internal Sources	3,464	1	
	Local Tributaries	1,788	10,052	

EPA/MPCA Required Elements	Summary	TMDL Page #
Margin of Safety	An explicit MOS of 20 percent has been applied as part of the LVR by setting the allowable loads to achieve a turbidity target of 20 NTUs rather than 25 NTUs. Additionally, a conservative value was used to adjust from NTRU to NTU-based reduction requirements for local tributaries and internal sources.	35
Seasonal Variation	Seasonal variation was addressed through the use of continuous modeling over a twelve-year period and by identifying load reductions that will achieve water quality standards during all seasons.	36
Reasonable Assurance	Meeting water quality standards in the LVR will require the development and implementation of the Lake Pepin TMDL; efforts to control sources internal to the LVR that might include wind-induced re-suspension of fine sediments, fish-induced re-suspension, and the draining of wetlands in the system following spring floods; and reducing loads from the local tributaries. There are a variety of practices, responsible parties, and sources of funding to accomplish these tasks, some of which are described in Section 7.1.	37 -43
Monitoring	A detailed monitoring plan has not been developed as part of this TMDL; however, general recommendations are made for continuing existing monitoring efforts and collecting new data regarding internal sources and the local tributaries.	43
Implementation	The following potential implementation activities are described: ▪ Water Level Management ▪ Fish Management ▪ Agricultural Best Management Practices A more detailed implementation plan is being developed by the Dakota County SWCD.	37-43
Public Participation	A "kickoff" public meeting for this project was held February 26, 2004 at the Hastings City Hall and another meeting was held November 30, 2006 in Farmington to present the results of Phases I and II of the study. A final public meeting was held on March 19, 2008 at the Pleasant Hill Library in Hastings to present the draft TMDL report and MPCA also will accept written comments on the draft report for a period of 30 days.	45

EXECUTIVE SUMMARY

The Lower Vermillion River (LVR) extends from Hastings, Minnesota, to the confluence of the Vermillion River and the Mississippi River south of Lock and Dam 3. Water quality monitoring of the LVR has shown that turbidity levels exceed the Minnesota Pollution Control Agency's (MPCA) water quality standard approximately 40 percent of the time. As required by the Clean Water Act, MPCA has developed this Total Maximum Daily Load (TMDL) report to identify the activities that need to occur to address the turbidity impairment.

The goals of the LVR Watershed Turbidity TMDL Project are to describe the nature and extent of turbidity in the highly complicated setting of the LVR, determine turbidity source load allocations that consider major sources, and produce this final report that expresses the turbidity dynamics in terms of an "allocation" among sources and recommendations for corrective actions. Because of the complexities of the system, the project was implemented in three phases:

- Phase I: Data Gathering and Conceptual Model Development
- Phase II: Sampling and Model Setup
- Phase III: Model Refinement and TMDL Development

This report documents the results of the Phase III analysis, with the Phase I and II findings included as Appendices A and B, respectively.

The LVR system is hydrologically complex with the LVR having a naturally low gradient and occupying the floodplain of the Mississippi River. Flow enters this system from the Upper Vermillion at Hastings, via local tributaries, through movement of groundwater; and by interflow with the Mississippi. The last component is particularly important to understanding the LVR. Because of the operation of Mississippi Lock and Dam 3 for navigation, normal pool in Mississippi Pool 3 is typically greater than 5 feet above the water surface elevation in the LVR. This creates a tendency for water from the Mississippi to flow into the LVR, seeking steeper gradient to the channel below Lock and Dam 3. It also creates a positive groundwater gradient from the Mississippi to the LVR. Finally, because of its own low channel gradient, flow within the LVR can be affected by the water surface elevation at its confluence with the Mississippi, below Lock and Dam 3, and by flows in the Cannon River.

The local watershed of the LVR, the LVR channel, the Upper Vermillion River, and Mississippi Pool 3 are all sources of loads of sediment and organic material that contribute to turbidity. In addition, phosphorus loads are important because they may promote algal growth in the LVR. The following inferences have been made as a result of this study regarding the high turbidity observed in the LVR:

- Inorganic sediment appears to be the primary cause of elevated turbidity.
- Pathways involving algae and organic detritus are generally of lesser significance to turbidity in the LVR, but they do provide a contribution.
- External loads of algae and detritus to the LVR are likely not significant contributors to the turbidity problem.
- Algal growth within the LVR is a secondary, although not the major, contributor to turbidity.

During Phases II and III of this study the U.S. Army Corps of Engineers CE-QUAL-W2 model was applied to provide a more complete description of the movement of water and sediment in the LVR system and to link sediment sources with turbidity impacts. The model was first calibrated to the observed data and then used to evaluate the most significant sources of sediment to the LVR and the load reductions and other activities necessary to achieve water quality standards.

The CE-QUAL-W2 modeling determined that the largest source of sediment to the LVR is Pool 3 via the various sloughs that connect the two waterbodies. Truedale Slough is estimated to contribute about 35 percent of the average annual sediment load and Carter and Vermillion Sloughs are estimated to contribute another 21 and 16 percent, respectively. The next most significant source of sediment was found to be the local tributaries draining from the LVR watershed (16 percent) followed by the Upper Vermillion River (8 percent). Internal sources of sediment, such as wind- and fish-induced re-suspension of fine sediments and the draining of wetlands, were estimated to contribute approximately 3 percent of the sediment load; however, despite the relatively small load contribution from these sources, they were found to have a significant impact on turbidity during periods when there is little inflow from Pool 3. Less than one percent of the load originates from Mississippi Pool 4.

The TMDL allocation results for the LVR were arrived at by using the calibrated model to determine the load reductions necessary to achieve water quality standards. The achievement of water quality standards was defined as having the 30-day average turbidity values at a variety of assessment points be less than 20 NTU over the modeling period. The analysis found that the following combination of activities is predicted to result in achieving water quality standards:

- Turbidity in Pool 3 must be reduced such that it achieves a 30-day average turbidity of 20 NTU. This approximates the turbidity goal for Pool 3 required by the Lake Pepin TMDL.
- Loads from internal sources must be reduced by 50 percent.
- Local tributary loads must be reduced by 33 percent.

No load reductions are necessary for the Upper Vermillion River, although the planned movement of the Empire wastewater treatment plan effluent to the Mississippi River is expected to have a beneficial impact on water quality within the LVR. Despite the fact that no load reductions are required for these sources, a load allocation for the Upper Vermillion River and wasteload allocations for its NDPES permitted municipalities (MS4s) were computed to meet the requirements of a comprehensive TMDL.

Based on these findings, implementation of the LVR TMDL will need to include several components:

- Continued development and then implementation of the Lake Pepin TMDL to ensure Pool 3 achieves water quality standards.
- Implementation of water level management aimed at reducing internal sources of sediment loads.
- Adoption of a variety of agricultural and urban controls within the LVR watershed, such as increased use of conservation tillage, grade stabilization structures to control gully erosion, and various practices associated with innovative stormwater management and better site design.
- No increase in loading from the Upper Vermillion River, including its MS4s.

1.0 INTRODUCTION

The Clean Water Act, Section 303(d), requires that states publish, every two years, a list of waters that do not meet water quality standards and do not support their designated uses. These waters are then considered to be “impaired”. Once a waterbody is placed on the impaired waters list, a Total Maximum Daily Load (TMDL) must be developed. The TMDL provides a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards. It is the sum of the individual wasteload allocations (WLAs) for permitted point sources, load allocations (LAs) for nonpoint sources and natural background sources, plus a margin of safety (MOS). U.S. Environmental Protection Agency (EPA) guidance requires that TMDLs be expressed in terms of allowable loads in daily time increments (USEPA, 2006).

The Lower Vermillion River (LVR) extends from Hastings, Minnesota, to the confluence of the Vermillion River and the Mississippi River south of Lock and Dam 3 (Figure 1-1). Water quality monitoring of the LVR has shown that its turbidity levels frequently exceed the Minnesota Pollution Control Agency’s (MPCA) standard of 25 nephelometric turbidity units (NTU). As required by the Clean Water Act, MPCA has conducted a study to determine the activities that need to occur to address the turbidity impairment; this report summarizes the results of the TMDL study. The Section 303(d) listing information for the Lower Vermillion River is shown in Table 1-1.

Table 1-1. 2008 303 (d) List Information for the Lower Vermillion River Watershed.

Waterbody Name	Waterbody Description	River ID	Cause of Impairment	Impaired Designated Use
Vermillion River	Vermillion R/Vermillion Slough, Hastings dam to Mississippi R	07040001-504	Turbidity	Aquatic Life

Turbidity is a measure of water clarity. When turbidity is elevated, the water appears cloudy and visibility is reduced. In addition to aesthetics, elevated turbidity has adverse impacts on aquatic life. For example, elevated turbidity reduces the ability of sight-feeding gamefish to find their prey and reduces the vigor of the submerged aquatic vegetation that forms the basis of a healthy ecosystem in most Minnesota rivers. Elevated turbidity can be caused by a number of factors, including loads of fine sediment, growth of microscopic floating algae exacerbated by nutrient loads, and dissolved organic material.

The goals of the LVR Watershed Turbidity TMDL Project are to describe the nature and extent of turbidity in the highly complicated setting of the LVR, determine turbidity source load allocations that consider major sources, and produce this final report that expresses the complicated turbidity dynamics in terms of an “allocation” among sources and recommendations for corrective actions. Because of the complexities of the system, the project was implemented in three phases:

- Phase I: Data Gathering and Conceptual Model Development
- Phase II: Sampling and Model Setup
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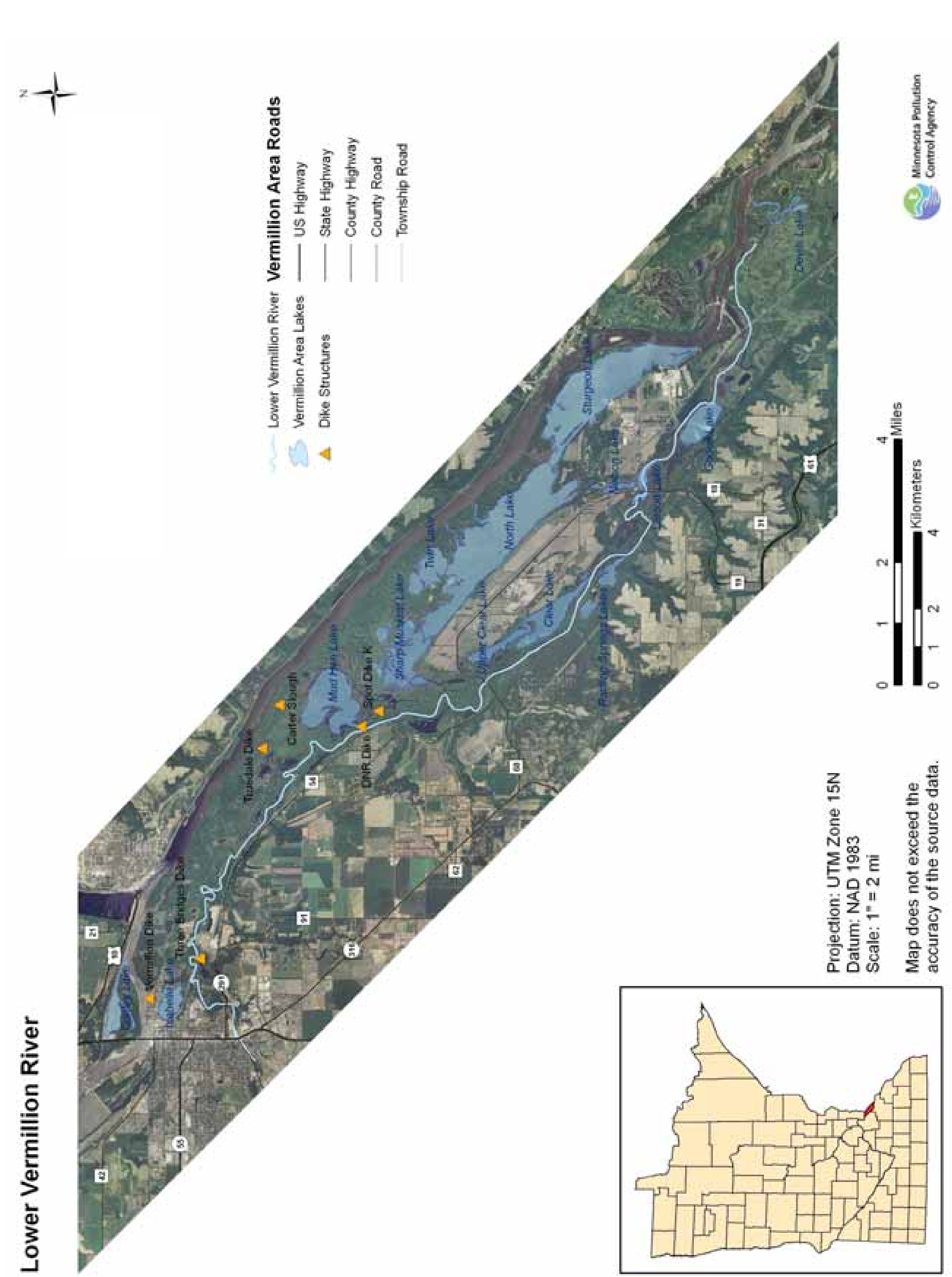

Figure 1-1. The Lower Vermillion River.

2.0 WATERSHED BACKGROUND

The Vermillion River travels approximately 59 miles from its headwaters in southeastern Scott County near New Market to the confluence with the Mississippi River south of Lock and Dam 3. The entire Vermillion River watershed drains about 356 square miles and consists of 17 subwatersheds (Figure 2-1).

Below the Old Peavey Mill Dam in Hastings (downstream of the falls), the Vermillion River splits. One branch (Vermillion Slough) flows to the north to join the Mississippi River near mile 813, and the other branch flows to the south to join the floodplain of the Mississippi River. The floodplain of the LVR and Mississippi River is known as the Vermillion River Bottoms. On this alluvial floodplain, the LVR parallels the Mississippi River for approximately 20 miles before joining it just downstream from Lock and Dam 3 near Red Wing, Minnesota. The LVR watershed consists of two subwatersheds draining approximately 77 square miles (Figure 2-1).

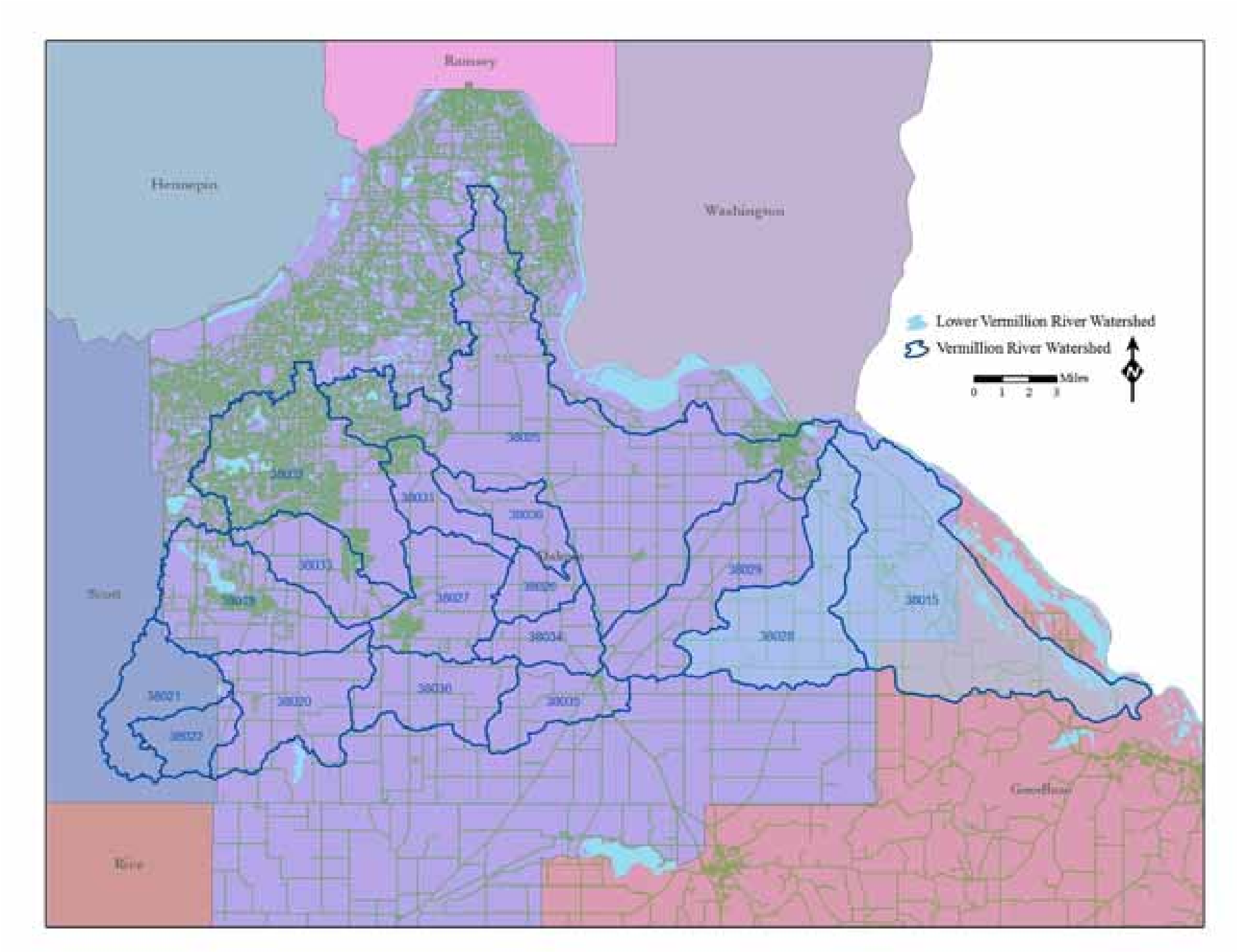

Figure 2-1. Vermillion River watershed boundaries.

2.1 Historical Conditions

Modifications of the hydrologic regime of the LVR have had significant impacts on the suspended solids load and the associated turbidity. The most notable change is associated with the impoundment of Mississippi Pool 3, beginning in 1936, which raised the stage of the Mississippi and created a tendency for water to flow from the Mississippi into the LVR. Many of the other changes have occurred since 1938, the date of the earliest aerial photos. However, alterations to the floodplain and hydrology can also be observed in those historic photos. For example, in the aerial photograph taken on July 18, 1938 several cleared areas (possibly row crops or pasture land) can be observed on Prairie Island. This photograph also suggests that the LVR appeared to carry a very high sediment load. This sediment would have been deposited on the floodplain during flood stage events, and the accumulation of excessive sediment in the channel caused the development of channel bars and islands, some of which were substantially vegetated. The gradient change in the slope of the landscape and stream is very low, and the river has a high sinuosity pattern and appears to be prone to migration during channel-forming bankfull flood events under natural conditions.

The confluence of the LVR and the Mississippi River is characteristic of a large delta fan. In the 1983 photos the LVR appears to be separated from the Mississippi River mainstem by a low-elevation natural levee, created by the deposition of excess sediments as the Mississippi River and LVR expand over their banks into the floodplain, drop stream velocity, decrease in energy, and deposit sediment. These natural deposits and levee formations extend along the floodplain of the Mississippi River, causing the LVR and Mississippi River to run parallel for some distance before they finally merge. As flood stages increase, the water levels rise over these natural levees, channel bars, and the land mass separating the LVR and Mississippi River. Several depressions in these near-stream land masses become inundated with large amounts of floodwaters and then gradually subside in stage as evaporation and groundwater percolation occurs. Some minimal permanent flow is present in the larger floodplain; there the elevation of the pond bottom is low enough to intersect the groundwater table, which is maintained at a high elevation by the impoundment of Pool 3.

Use of the nearby floodplains as agricultural lands in the 1920’s and 1930’s potentially could have lead to increased sediment inputs into the river. A 1938 aerial photograph shows the confluence of several tributaries with the LVR and indicates that large sediment loads were deposited at these confluences as alluvial deposits. Closer scrutiny shows large sediment deposits in the channel of the LVR just below the surface, along with several large bar developments.

Aerial views of the same section of the LVR near Carter Slough and Mud Hen Lake in 1938, 1992, and 2000 indicate that during this time span there appears to be a shift from agricultural land uses to residential development along the bluffs. The vegetative characteristics of the ponds appear to change, and the stage levels of the ponds seem to have become more permanent. Man-made structures have also developed to further control the hydrology of the river systems during regular and flood stages.

In conclusion, construction of Lock and Dam 3 is the most important human activity affecting water quality within the LVR. However, a review of historic aerial photos reveals that the LVR was modified and influenced by human impacts even prior to construction of Lock and Dam 3. Since 1938 the LVR has undergone even more significant anthropogenic influences and changes to the hydrology, channel morphology, and floodplain corridor. The hydrology is very dynamic and complex, with subsurface flows and surface channels interconnected to the various ponds and rivers. The LVR appears to carry a large sediment load, which it deposits into bars and onto the floodplain during greater-than-bankfull flood events.

2.2 Current Conditions

The sections below provide information on the land use/land cover of the LVR watershed as well as current hydrologic conditions. More detailed information on the LVR is included in Appendix A and Appendix B.

2.2.1 Land Use/Land Cover

Figure 2-2 shows the eight land use classes defined for the LVR watershed and the distribution of land use/land cover is summarized in Table 2-1. Land use/land cover is approximately (rounded to nearest percentile) 57 percent agriculture (corn, soybean, and pasture), 26 percent forest, 9 percent urban, and 8 percent "other" (e.g., wetlands, water). The majority of the agricultural lands are devoted to growing corn and soybeans, and approximately half of the corn-soy rotation is in conservation tillage (personal communication from Brad Becker, Dakota County Soil and Water Conservation District to Kevin Kratt, Tetra Tech, September 25, 2006).

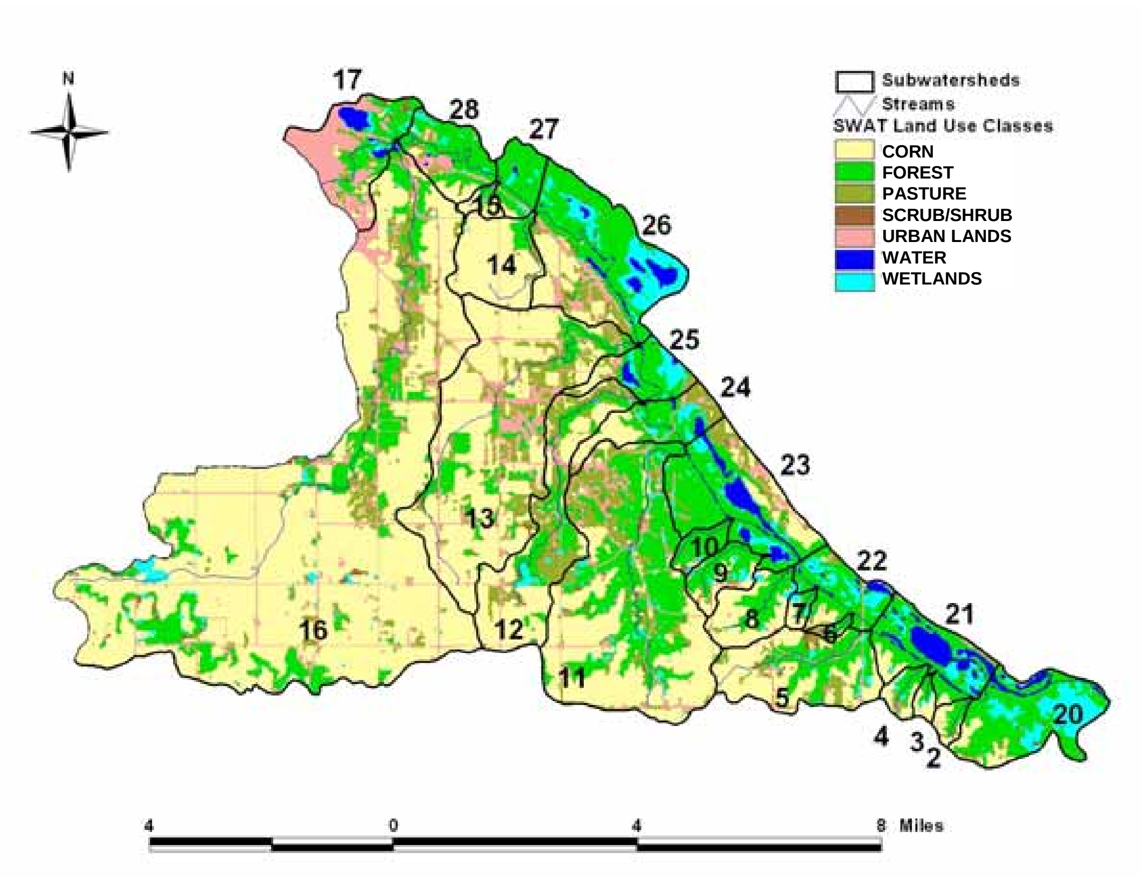

Figure 2-2. Land Use Classification for the Lower Vermillion Watershed. Note that the mapped CORN class includes the interpreted CORN and MULCH land uses.

Table 2-1. Land use/land cover in the Lower Vermillion River watershed.

Description	Acres	Square Miles	Percentage
Medium Density Urban Land	4244	6.6	8.6 percent
Conventional Corn-Soy Rotation	11633	18.2	23.5 percent
Corn-Soy Rotation with Mulch Tillage	11633	18.2	23.5 percent
Pasture and Hay	4746	7.4	9.6 percent
Deciduous Forest	13093	20.5	26.4 percent
Water	1092	1.7	2.2 percent
Wetland	2547	4.0	5.1 percent
Scrub/Shrub	561	0.9	1.1 percent
TOTAL	49,549	77.5	100.0 percent

Notes: Table shows the land use/land cover used for the Soil and Water Assessment Tool (SWAT) modeling. See Appendix B for more details regarding the origin of the land use/land cover data.

2.2.2 Hydrology

The LVR system is hydrologically complex. The Lower Vermillion occupies the floodplain of the Mississippi River and has a naturally low gradient. Flow enters this system from the Upper Vermillion at Hastings, Minnesota; via local tributaries, through movement of groundwater; and by interflow with the Mississippi. The last component is particularly important to understanding the LVR. Because of the operation of Mississippi Lock and Dam 3 for navigation, normal pool in Mississippi Pool 3 is typically greater than 5 feet above the water surface elevation in the LVR. This creates a tendency for water from the Mississippi to flow into the LVR, seeking steeper gradient to the channel below Lock and Dam 3. It also creates a positive groundwater gradient from the Mississippi to the LVR. Finally, because of its own low channel gradient, flow within the LVR can be affected by the water surface elevation at its confluence with the Mississippi, below Lock and Dam 3, and by flows in the Cannon River.

High Water Inundation in Vermillion River Floodplain Forest. July 2001

The interchange of water between the LVR and Mississippi Pool 3 depends on the relative stage in the two systems. Conditions can be broadly separated into two modes according to stage at the Prescott gage in Pool 3 of the Mississippi River and the corresponding relative importance of Pool 3 intrusions into the LVR. Mode 1 implies that Mississippi River inflows dominate conditions in the Lower Vermillion, while Mode 0 implies that significant inflow from the Mississippi does not dominate. When stage at Prescott is above about 676’ there is strong inflow from Pool 3 into the LVR (inflow begins at about 675.2’, but does not exceed the normal flow from the Upper Vermillion River until reaching about 676’), and days meeting this condition are designated as Mode 1. All other days are assigned Mode 0. Mode 0 occurs about 214 days per year (58.5 percent) and Mode 1 occurs about 151 days per year (41.5 percent). Characterizing the hydrology in this manner is roughly equivalent to creating a “two zone” flow duration curve for the system to serve as the basis for the modeling and TMDL allocations.

Vermillion River at Etter Bridge. November 2003 (Mode 0 Conditions)

On a long-term basis the LVR system appears to receive significantly more inflow from Mississippi Pool 3 than from the Upper Vermillion. Even when estimates of inflow from local tributaries to the LVR and groundwater discharge are added, the long-term inflow from Pool 3 is still more than twice the flow from other sources. Cumulative loading to the LVR (of water and pollutants) thus depends largely on the Mississippi. During low to moderate flow conditions, however, inflow to the LVR can be dominated by the river’s own watershed. Additional detailed discussion of the hydrology of the LVR is provided in Appendix A.

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3.0 WATER QUALITY STANDARDS AND REVIEW OF AVAILABLE DATA

The purpose of a TMDL is to identify the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards. As such, it is very important to understand the water quality standards that apply to the impaired waterbody. This section of the report provides information on the water quality standards that are relevant to the LVR turbidity TMDL.

3.1 Water Quality Standards

Minnesota adopted its first statewide water quality standards in 1967. These standards have been updated by adding new standards and regulations periodically since then. The comprehensive Clean Water Act amendments of 1972 require states to adopt water quality standards that meet the minimum requirements of the federal Clean Water Act and Minnesota's water quality standards meet or exceed the federal requirements.

Under the Clean Water Act, every state must adopt water quality standards to protect, maintain, and improve the quality of the nation's surface waters. These standards represent a level of water quality that will support the Act's goal of "fishable and swimmable" waters. Water quality standards consist of three components: beneficial uses, numeric or narrative standards, and a nondegradation policy. Minnesota's water quality standards are summarized in Table 3-1 and explained in greater detail below.

Table 3-1. Minnesota Water Quality Standards

Component	Description
Beneficial use	Beneficial uses are the uses that states decide to make of their water resources. The process of determining beneficial uses is spelled out in the federal rules implementing the Clean Water Act.
Numeric standards	Numeric water quality standards represent safe concentrations in water that protect a specific beneficial use. If the standard is not exceeded, the use should be protected.
Narrative standards	A narrative water quality standard is a statement that prohibits unacceptable conditions in or on the water, such as floating solids, scums, visible oil film, or nuisance algae blooms. Narrative standards are sometimes called "free froms" because they help keep surface waters free from fundamental, basic types of water pollution.
Nondegradation	(equivalent to the federal term "antidegradation"). The fundamental concept of nondegradation is that lakes, rivers, and streams whose water quality is better than the applicable standards should be maintained at that high level of quality and not allowed to degrade to the level of applicable standards.

Water quality standards and related provisions can be found in several Minnesota rules, but the primary rule for statewide water quality standards is Minnesota Rules Chapter 7050. Included in this rule are the following:

- A classification system of beneficial uses for both surface and groundwaters
- Numeric and narrative water quality standards
- Nondegradation provisions
- Provisions for the protection of wetlands
- Treatment requirements and effluent limits for wastewater discharges
- Other provisions related to protecting Minnesota's water resources from pollution

Although portions of the Vermillion River upstream of Hastings are designated Class 2A (trout streams), the LVR is not specifically listed in the rules and therefore has a default classification of 2B.

The Minnesota Rules specify that Class 2B surface waters must permit the propagation and maintenance of a healthy community of cool or warm water sport or commercial fish and associated aquatic life and their habitats. The chronic turbidity standard for Class 2B waters is 25 NTU [Minnesota Administrative Rules. 7050.0220. Subpart. 4a]. A value of 20 NTU was used as the target for the LVR TMDL for two reasons:

1. To be consistent with research showing this value is appropriate for re-establishing vegetation (UMRCC, 2003).
2. To add a 20 percent margin of safety.

3.2 Biological Data

During Phase I of the TMDL study a variety of agencies were contacted in an attempt to compile biological and related data for the LVR, including MPCA, the Minnesota Department of Natural Resources (MDNR), and the U.S. Fish and Wildlife Service. Appendix A provides more detail on the information that was obtained.

MDNR has collected aquatic vegetation data for the Vermillion River system since 1995. MDNR reports indicate that much of the system is devoid of any aquatic vegetation. When vegetation is present, biodiversity is low and the species present are considered common. Some species present, such as curly pondweed (*Potamogeton crispus*), are even considered “ecologically invasive” (Hoffman, 1997). Notable exceptions include sightings of horned pondweed (*Zannichellia palustris*), which is endangered in Indiana and rare in northeastern states. Wild rice (*Zizania aquatica*) was also noted in some of the off-channel lakes.

MDNR has also used these aquatic plant data in the development of an “Aquatic Habitat Quality Index Summary.” This index is based on a qualitative assessment of aquatic vegetation diversity and density, bathymetric diversity, substrate composition, and water quality. Index values calculated for the Vermillion River system indicate that the majority of the system is characterized as fair to poor. On-channel lakes such as Larson and Birch, as well as large backwater lakes like Clear and Goose, consistently scored in the poor to very poor range. In contrast, Rattling Springs and Jones Lakes, two smaller, off-channel waterbodies close to the bluffs, consistently scored in the good range.

MDNR collected fisheries survey data in the LVR system from 1995 to 2000 and additional data has been collected since 2002. The data were collected by either the seining or electrofishing method. Electrofishing was conducted with the intent of monitoring some of the important game-fish species known to occur in the system and comparing their populations from year to year. These year to year data are best summarized with a catch per unit effort (CPUE).

Electrofishing data from the Mississippi River Pool 3 were used as a comparison to the Vermillion electrofishing data. CPUE rates were consistently higher in the Lower Vermillion than in the Mississippi, indicating that these particular game-fish populations in the Vermillion River are generally healthy. This conclusion is supported by an MDNR report, which states, “Fish populations are generally healthy and appear stable. This is significant, considering that suspended solids within the water column reduce Secchi readings to less than one foot throughout most of the open-water period” (Dieterman, 2002). The data, as well as the MDNR report, offer surprising results: despite some indications of poor water quality in the system (including turbidity in excess of 25 NTU), some game-fish populations are strong.

Although some fish species in the LVR appear to be healthy, qualitative evidence suggests that high turbidity levels might be affecting other species in the LVR. For example, local residents have reported to MDNR that aquatic vegetation was historically more abundant, and anglers in the area report catching fair amounts of yellow perch. Yellow perch are now found only in very small numbers in the Vermillion system. Research has shown that yellow perch are more susceptible to negative effects from turbidity and sedimentation than some other game-fish species (Newcombe et al., 1996).

In summary, there are limited data with which to fully characterize the current health or trends of the LVR aquatic communities. Furthermore, aquatic health is affected by a variety of factors other than water quality and habitat, such as immigration/emigration, intra- and interspecific competition, and predation. The data do suggest, however, that the Vermillion River and its associated lakes are supporting fair populations of game-fish species and that there appear to be some pieces of excellent aquatic life habitat within a system that is poor overall.

3.3 Turbidity Data

Turbidity in the water column results from a combination of inorganic sediment, living algae, organic detritus, and color associated with dissolved organic compounds. The local watershed of the LVR, the LVR channel, the Upper Vermillion River, and Mississippi Pool 3 are all sources of loads of sediment and organic material that contribute to turbidity. In addition, phosphorus loads are important because they may promote algal growth in the LVR. A general conceptual framework for turbidity in the LVR was derived during Phase I and is shown in Figure 3-1. The figure connects stressor sources (at the bottom) with the management target, turbidity, at the top. Each individual pathway (bottom to top) through the diagram can be considered a risk hypothesis for elevated turbidity.

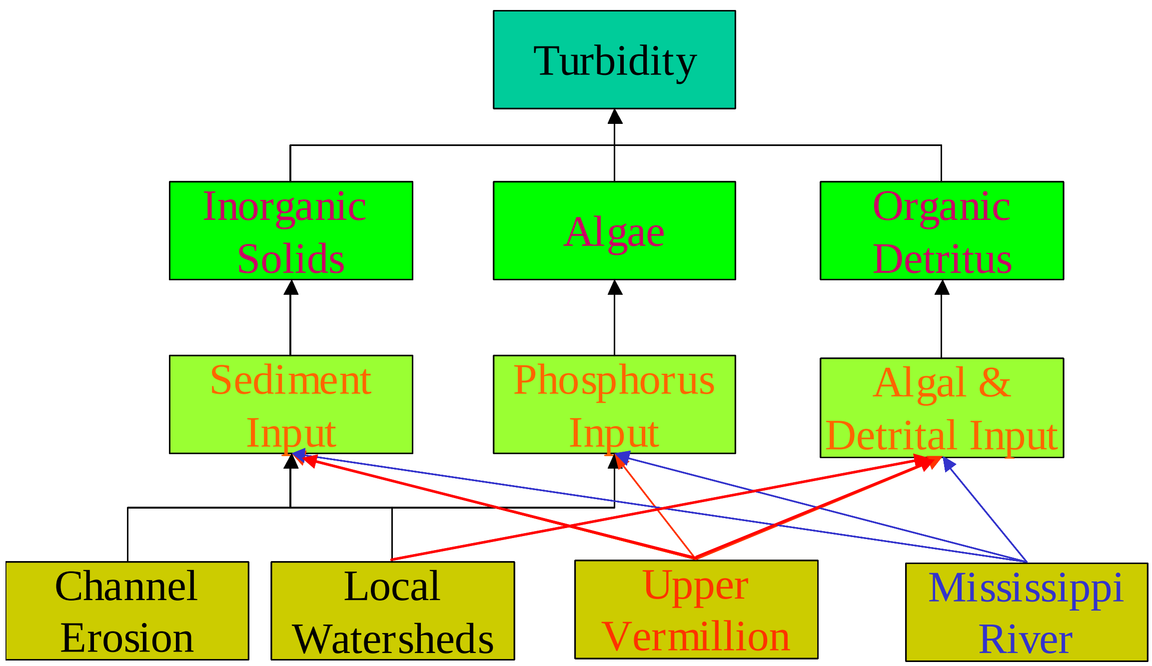

Figure 3-1. General conceptual model of turbidity in the LVR.

All the pathways through this diagram are of potential importance; however, some are clearly more important than others. The following inferences have been made as a result of this study:

- Inorganic sediment (measured as Inorganic Suspended Solids or ISS) appears to be the primary cause of elevated turbidity (Appendix A). This suggests that the risk pathways through the box "Sediment Input" in Figure 3-1 are the most important.
- Pathways involving algae and organic detritus (measured as Volatile Suspended Solids or VSS) are generally of lesser significance to turbidity in the LVR, but they do provide a contribution (about 38 percent of turbidity on average arises from all volatile solids).
- Volatile suspended solids do not appear to be a significant component of turbidity in Mississippi Pool 3. External loads of algae and detritus to the LVR are likely not significant contributors to the turbidity problem.
- Algal growth within the LVR is a secondary, although not the major, contributor to turbidity. The removal of the Empire WWTP loads from the LVR is expected to further lessen the importance of algal growth within the LVR on turbidity conditions.

Turbidity data have been collected at several stations along the LVR (Figure 3-3) and Table 3-2 provides a summary of the available data for all stations with a minimum of five samples. The table indicates that approximately 40 percent of the samples at the confluence with the Mississippi River have exceeded 25 NTU. The exceedance percentage at the confluence with the Mississippi River are fairly equal between Mode 0 (Minimal Pool 3 Inflow) and Mode 1 (significant Pool 3 inflow). Figure 3-2 indicates that there is no discernible temporal trend over the period of record.

Table 3-2. Summary of turbidity data available for the Lower Vermillion River Watershed.

Location (Station)	Period of Record	Number of Samples	Min (NTU)	Average (NTU)	Median (NTU)	Std Dev (NTU)	Max (NTU)	Mode 0 >25 NTU	Mode 1 > 25 NTU
LVR 1 mile upstream of confluence with Cannon River (MS221)	4/30/1990 to 9/28/1992	54	2.0	26.4	26.2	13.2	51.1	75 percent	38 percent
LVR 5 miles southeast of Hastings (MS297)	6/12/1995 to 11/16/2006	8	5.0	22.8	20.1	17.8	58.1	0 percent	100 percent
LVR at High 68 Bridge (MS299)	6/12/1995 to 11/16/2006	8	3.1	24.8	17.6	22.4	64.2	0 percent	100 percent
LVR at confluence with Mississippi River (VM00.1M)	1/24/1990 To 11/8/2006	405	2.0	21.6	19.0	15.8	89.0	37 percent	39 percent
LVR at River Mile 2 (VR002.0)	6/6/1994 to 12/30/1996	63	1.4	24.9	14.8	25.7	160.0	32 percent	37 percent

Notes: The data used to create this table are based on original turbidity data where reported or estimated turbidity using the equation Turbidity = $-1.098 + TSS^{0.974}$ (Appendix A Section 4.2.15). Only stations with more than 5 samples are included in the table.
The data for station MS221 on the LVR one mile upstream of the confluence with the Cannon River are dated (last sampling event is from 1992), but these are the only data available at this location.
Regarding turbidity at site VM00.1M: From 1988 to 1996, the Long Term Resource Monitoring Program (LTRMP) used Hach Model 16800 portable turbidimeters for turbidity measurements. In late 1996 the LTRMP replaced the Hach Model 16800 with the Hach Model 2100P. This note is considered and addressed in the following chapters.

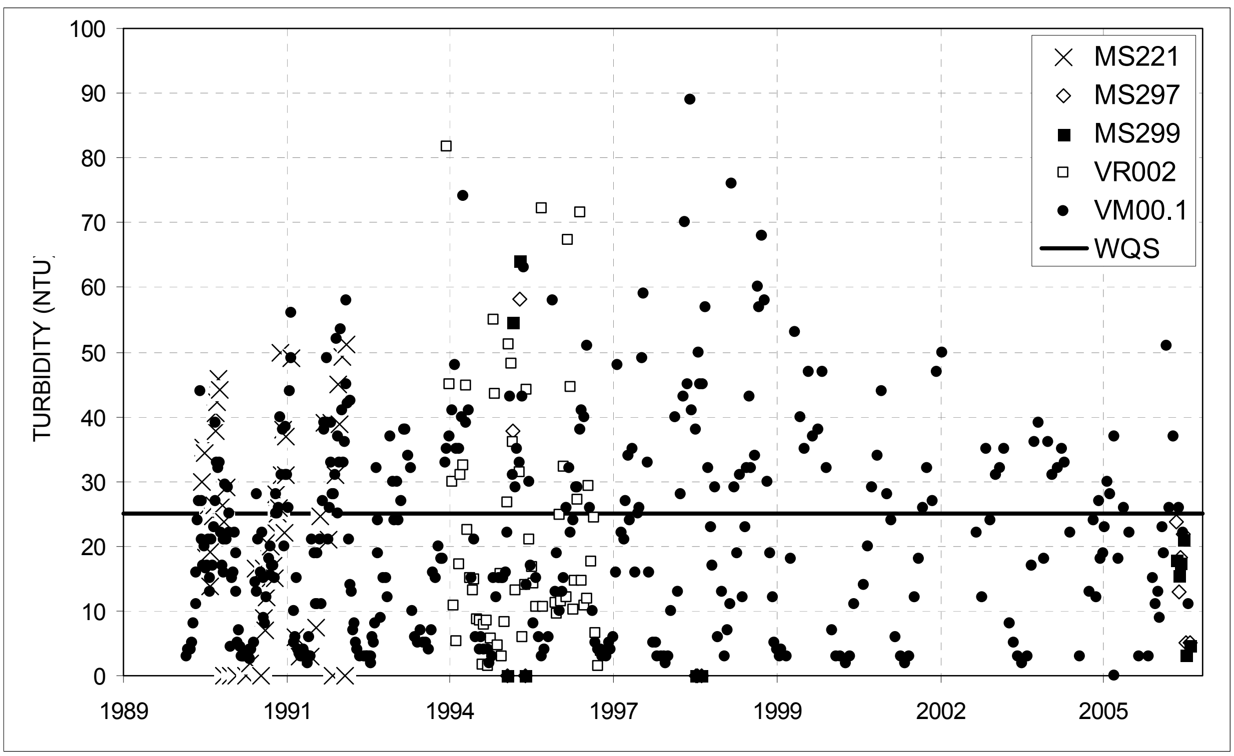

Figure 3-2. Available turbidity data for LVR monitoring stations.

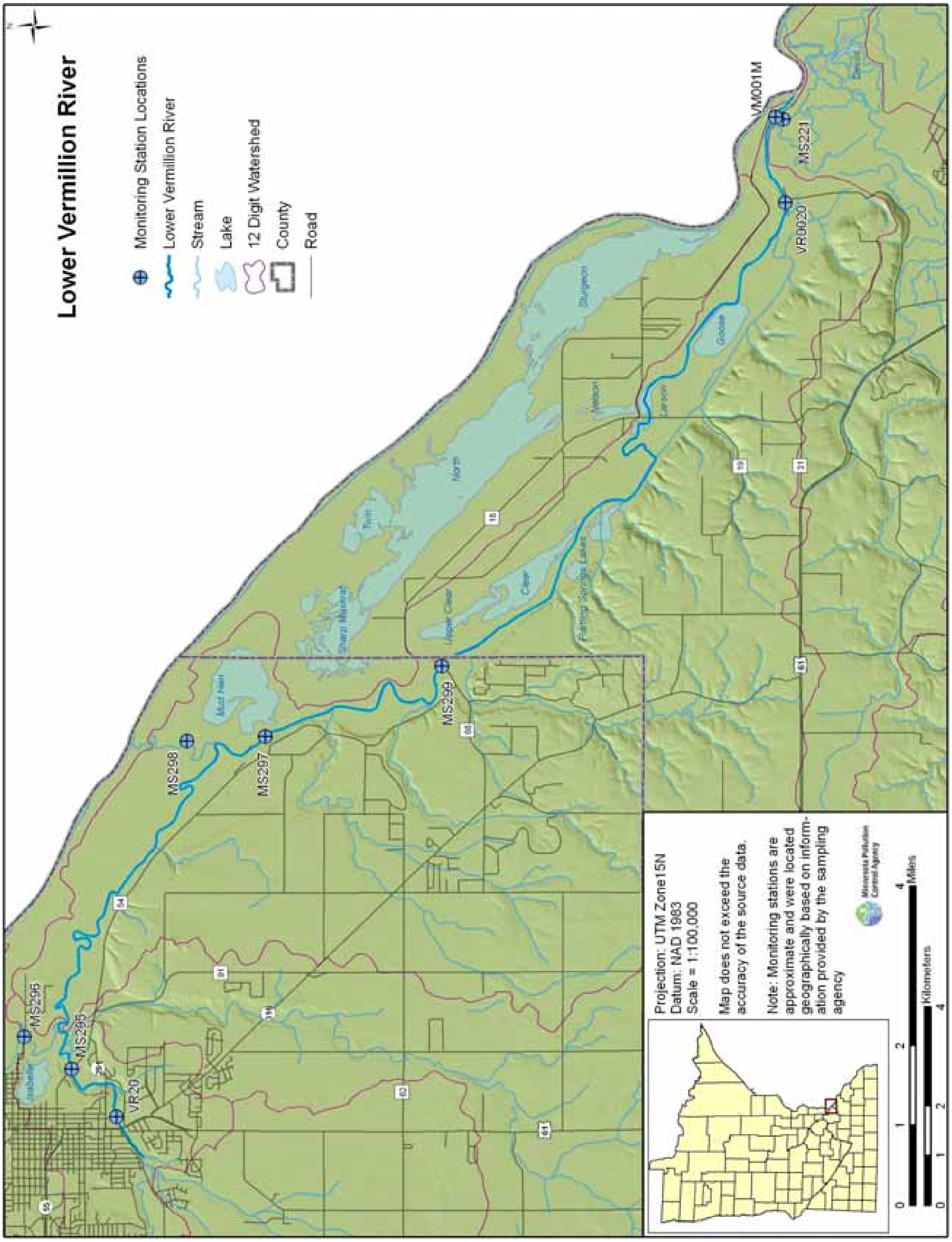

Figure 3-3. Location of water quality sampling stations in the LVR study area.

4.0 MODELING APPROACH AND RESULTS

One of the conclusions of the Phase I study (Appendix A) was that a model was needed to provide a more complete description of the movement of water in the LVR system and to link sediment sources with turbidity impacts. A secondary need was the creation of a model to evaluate the impact of nutrients and algae. The U.S. Army Corps of Engineers CE-QUAL-W2 (W2) model was chosen for this purpose and Phase II of the study focused on the setup and calibration of the W2 model.

W2 is a two-dimensional, longitudinal/vertical (laterally averaged), coupled hydrodynamic and water quality model (Cole and Wells, 2003). The model is applicable to lakes, rivers, and estuaries that do not exhibit significant lateral variability in water quality conditions. It allows the user to specify multiple branches for geometrically complex waterbodies, variable grid spacing, time variable boundary conditions, hydraulic structures, and multiple inflows and outflows from point/nonpoint sources and precipitation.

Advantages to choosing W2 for the Lower Vermillion River modeling application included the following:

- W2 is able to address the pollutants of concern (e.g., total suspended solids (TSS), inorganic suspended solids (ISS), total phosphorus (TP), NH4, nitrate+nitrite (NO2NO3), dissolved oxygen (DO), and chlorophyll *a* (CHLA)). These pollutants were in turn used to estimate turbidity using relationships identified during the Phase I analysis.
- W2 is appropriate for a long and narrow river with spatially varying depths.
- W2 has been successfully linked in previous applications to the Soil and Water Assessment Tool (SWAT), which is used to estimate pollutant loads from the local tributaries to the LVR.
- W2 is able to predict increased light availability due to a decrease in sediment.
- W2 provides the advantage of using a tested and widely accepted model – although some code modification was needed to address the simulation of total phosphorus (see Appendix B for details).
- W2 is capable of simulating cause-and-effect relationships between loading from various sources and river response.
- Application of W2 was consistent with the schedule and budget.

The LVR model calibration included two steps. The first step was to calibrate the hydrodynamic simulation which determines the flow and mixing coefficients for solute transport. After the hydrodynamics were calibrated, the water quality calibration was conducted without changing any of the coefficients related to the hydrodynamics simulation.

A twelve-year period (January 1, 1995 to December 31, 2006) was used for the hydrodynamic and water quality calibration to ensure that both low, average, and high flow conditions were included. Model results were primarily assessed by comparing model results with observed data. The locations where these comparisons were made are listed below and shown in Figure 3-2:

- Lower Vermillion River at Highway 54 (MS295)
- Vermillion Slough at E 4 Bridge (MS296)
- Lower Vermillion River 5 miles southeast of Hastings (MS297)
- Truedale Slough (MS298)
- Lower Vermillion River at Highway 68 Bridge (MS299)
- Lower Vermillion River at river mile 2 (VR002.0)
- Vermillion River at Mouth (VM00.1M)

The major values adjusted during the calibration process were the suspended solids settling rate, the phosphorus partition coefficient, and the parameters related to algae growth. The estimates of loads from the SWAT modeling of the local tributaries were also adjusted from the initial model runs to improve the calibration of TSS in the LVR. Loads were also added to the model during post-processing to account for internal sources for a similar reason (i.e., to improve the calibration results). In both cases there is qualitative evidence that local tributary and internal loads are important, but there are limited data with which to use as inputs to the model. Adjusting these loads during the W2 calibration process was therefore considered to be justifiable. The results of the model calibration are presented and further discussed in Appendix B.

5.0 SOURCE ASSESSMENT

This section of the report provides an overview and estimated magnitude of the various sources of sediment to the LVR.

5.1 Upper Vermillion River

In the Phase I Report (Appendix A), the USACE FLUX program (Walker, 1987) was used to convert estimates of flow and TSS concentrations in the Vermillion River at Hastings (the Upper Vermillion River) into daily load estimates. These data were available from the Metropolitan Council of Environmental Services (MCES) monitoring site at the ConAgra Mill near Highway 61 in Hastings. To support the Phase II modeling, the FLUX analyses were updated and recalculated through the end of water year 2006 (see Appendix B for details). The results are summarized in Table 4-1 and indicate that while the Upper Vermillion is a significant source of flow to the LVR, it contributes less than 10 percent of the fine sediment load. This is partly due to larger sediment particles from the Upper Vermillion settling out and being deposited as they enter the slower moving waters of the LVR.

Table 4-1. Summary of sediment loads to the LVR.

Source	Flow Volume		TSS Load		Method
	(m^3/yr)	Percent	(metric tons/yr)	Percent	
Upper Vermillion River	140,840,185	21.0 percent	2,298	7.8 percent	FLUX
Vermillion Slough	97,807,424	14.6 percent	4,852	16.5 percent	CE-QUAL-W2
Truedale Slough	208,303,719	31.0 percent	10,176	34.6 percent	CE-QUAL-W2
Carter Slough	140,770,856	21.0 percent	6,320	21.5 percent	CE-QUAL-W2
Local Tributaries	35,926,000	5.3 percent	4,791	16.3 percent	SWAT
Pool 4	9,516,025	1.4 percent	225	0.8 percent	CE-QUAL-W2
Internal Sources	38,598,768	5.7 percent	783	2.7 percent	Post-Processing
Total	671,762,977	100.0 percent	29,445	100.0 percent	

5.2 Local Tributaries to the LVR

The steep topography associated with the Mississippi bluffs can lead to high erosion potential and local direct tributaries, such as Etter Creek, contribute both flow and sediment load to the LVR. No data are available for these tributaries and their loads were therefore estimated using the Soil and Water Assessment Tool (SWAT) watershed model. Both upland (i.e., sheet and rill) and streambank erosion loads were estimated with SWAT and the resulting annual average loads are summarized in Table 4-1. The following important assumptions were made during the SWAT modeling:

- Based on information received from the Dakota County Soil and Water Conservation District, approximately half of the row crop (corn-soy rotation) agriculture was assumed to be in conservation tillage.
- The channel sediment routing component of SWAT was implemented as recommended in the SWAT manual, with most parameters set to defaults. Channel erodibility was set to 1/10 of the

surrounding soil erodibility, as recommended, and 20 percent of the channel was assumed to be without any vegetative cover or armoring protection from scour.

- Riparian buffers were assumed to be small in the upland areas (average of 1 meter); however, in the lowland floodplain areas much larger buffers were assigned (10 meters) to reflect the fact that there are typically wetlands, assumed to have significant trapping capability, between managed land and the Vermillion main channel.
- The initial estimates of loads from the SWAT modeling were adjusted downward to eliminate significant over-simulations of TSS concentrations within the LVR for certain short-term periods.

The SWAT model is uncalibrated (due to the lack of available data) but suggests that local tributaries are approximately 16 percent of the total TSS load into the LVR.

5.3 Loading from Mississippi River Pool 3

Three major sloughs are connected with Mississippi Pool 3 along the LVR, located at Mississippi River mile points 813.2 (Vermillion Slough), 808.5 (Truedale Slough), and 807.3 (Carter Slough). At the conjunctions of Pool 3 and the sloughs, water can flow freely and elevations in Pool 3 and the sloughs determine the magnitude and direction of the flow. Therefore, elevation boundary conditions were specified for the three sloughs within the W2 model. Measured elevations in Pool 3 are available for Mississippi River miles 815.0, 811.4, and 796.91 from the U.S. Army Corps of Engineers and linear interpolations of the elevations were used to estimate the Pool 3 elevations at the mouths of the three sloughs. The Pool 3 elevations then governed whether or not water was flowing from Pool 3 through the sloughs (or vice versa). Linear interpolation was used to estimate daily water quality concentrations for Pool 3 and these values were used along with the computed flows to estimate loads into the LVR. The results are summarized in Table 4-1 and indicate that Pool 3 is the most significant source of sediment to the LVR (approximately 70 percent).

5.4 Internal Sources

Several potentially significant sources of summer turbidity in the LVR are wind- and fish-induced re-suspension of fine sediments in the LVR lakes and the draining of wetlands in the system following the spring floods. For example, a study of Goose Lake (UMRSEMP, 1990), connected tangentially to the LVR, characterized the bottom substrate as consisting of unstable, fine material without submersed aquatic vegetation and wind-induced turbulent re-suspension was considered to be a major factor in elevated turbidity. The other lakes in the system that provide sufficient open fetch to develop wind-induced waves could also be important sources of turbidity to the LVR. It is also possible that the spring flood stores highly turbid water in the vast wetland areas of the LVR floodplain, and that this water gradually drains into the LVR during the summer and fall, maintaining high turbidity under non-event conditions. Additionally, the solids load in these shallow areas may be replenished by other disturbances in the wetland areas, such as rough fish activity. For example, studies have demonstrated that carp can significantly increase turbidity through the resuspension of bottom sediments compared to benthic fish native to North America (Parkos et al., 2003).

Re-suspension and the phenomenon of storage and release of solids load in wetland areas are not readily handled in the W2 model. Therefore, the missing load component was handled in post-processing of the model. Specifically, the original model output underpredicted turbidity during low-to-moderate flow conditions following the spring flood and persisting into the fall. After some experimentation, it was determined that the missing load component was best represented by adding a fixed concentration of inorganic suspended solids to the system during the summer and fall (see Appendix B for details). The results indicate that this added source contributes approximately 3 percent of the sediment load on an annual basis. As discussed in Section 6.0, despite the relatively small load contribution from this source, it has a significant impact on turbidity during periods when there is little inflow from Pool 3 (Mode 0).

5.5 Mississippi Pool 4

LVR enters Pool 4 of the Mississippi River and Pool 4 is the downstream boundary in the W2 model. The Pool 4 elevations impact the hydrodynamics of the LVR and Pool 4 was therefore a source of both flow and pollutant loading into the W2 model. Water quality data collected at Mississippi River Mile 796.9 were used to estimate the boundary conditions and the results are summarized in Table 4-1. They indicate that Pool 4 contributes only a minor load of sediment to the LVR.

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6.0 TMDL DEVELOPMENT AND DETERMINATION OF ALLOCATIONS

A TMDL is the total amount of a pollutant that can be assimilated by the receiving water while still achieving water quality standards. TMDLs are composed of the sum of individual wasteload allocations (WLAs) for point sources and load allocations (LAs) for nonpoint sources and natural background levels. In addition, the TMDL must include a margin of safety (MOS), either implicitly or explicitly, that accounts for the uncertainty in the relationship between pollutant loads and the quality of the receiving waterbody. TMDLs can also optionally be developed with a Future Growth Reserve for watersheds that are experiencing significant population growth. Conceptually, this is defined by the equation:

$$\text{TMDL} = \text{WLA} + \text{LA} + \text{MOS} + (\text{Future Growth Reserve})$$

The TMDL for the LVR watershed is presented in this section of the report; it was derived by using the calibrated W2 model to determine the allocations necessary to achieve the TMDL target. The modeling period was based on the same weather and hydrologic conditions as the calibration period, January 1, 1995 to December 31, 2006, and the following locations were used as assessment points (Figure 3-3):

- LVR 5 miles southeast of Hastings (MS297)
- LVR at High 68 Bridge (MS299)
- LVR at River Mile 2 (VR002.0)
- LVR at confluence with Mississippi River (VM00.1M)

The model runs with a maximum time step of 60 seconds (i.e., the model calculates flow and water quality conditions at least every 60 seconds) and therefore model output is theoretically available at this frequency. Since that volume of model output would be overly burdensome, model predictions were obtained twice daily (every 12 hours) and used to calculate daily average turbidity values. The daily average turbidity values were in turn used to calculate running 30-day average turbidity values to compare to the TMDL target.

Through iterative model runs the following combination of loads was found to achieve an average 30-day turbidity value of less than 20 NTUs at each assessment point. Note that the first two loads (from Pool 3 and the Upper Vermillion River) were not reduced during the iterative model runs. The load from Pool 3 to the Lower Vermillion River was set to approximate that which would result from Pool 3 meeting the turbidity goal put forth by the Lake Pepin TMDL, and therefore remained static. The Upper Vermillion River exceeds the turbidity standard only ~2 percent of the time and has little controlling impact on the Lower Vermillion system; therefore no load reduction is required from that boundary condition, and thus its load remained static. The third and fourth loads listed here (internal sources and local tributaries) were the focus of the iterative reductions as the model's goal was pursued at the four assessment points.

- Turbidity in Pool 3 was simulated as achieving water quality standards based on the assumption that this will occur at some point in the future due to the ongoing Lake Pepin TMDL and related efforts. Daily ISS and chlorophyll *a* values for Pool 3 were therefore reduced until they resulted in average 30-day turbidity values of less than 20 NTUs. These new daily values of ISS and chlorophyll *a* corresponded to an approximately 78 percent reduction in the load from Pool 3 that was simulated as entering the LVR.
- No reductions were made to the Upper Vermillion River loads as the turbidity in the Upper Vermillion River is currently meeting water quality standards. However, a new load estimate for the Upper Vermillion River was created to reflect the fact that the Empire WWTP that used to discharge to the Vermillion River at RM 15.6 was re-routed to the Mississippi River in early 2008 (Personal communications with Travis Bistodeau, Dakota County Soil and Water

Conservation District, January 22, 2008). Please refer to Appendix C for a discussion of how the new load estimate for the Upper Vermillion River was established.

- Loads from internal sources such as wind- and fish-induced re-suspension and wetland drainage were iteratively reduced during Mode 0 conditions until water quality standards were achieved in the LVR. A 50 percent load reduction (during Mode 0 conditions) was necessary to accomplish this.
- Local tributary loads required a reduction of 33 percent.
- Pool 4 loads did not need to be reduced.

The results of this model run indicate that LVR would meet the turbidity target at all assessment points. This suggests that the primary reason for the existing turbidity impairment during Mode 0 is the influence of internal sources and local tributaries and the primary reason for the existing turbidity impairment during Mode 1 is due to the influence of Pool 3. The final model run allocations are summarized in Table 6-1.

Table 6-1. TSS Allocation Summary (final model run).

Allocation Component: Source	Mode 0 (Minimal Pool 3 Inflow)			Mode 1 (Significant Pool 3 Inflow)		
	Existing TSS Load (kg/day)	Allowable TSS Load (kg/day)		Existing TSS Load (kg/day)	Allowable TSS Load (kg/day)	
TMDL= LA+WLA+MOS	**12,117**	**3,734**		**234,993**	**66,970**	
LA: UVR	1,478	1,478		9,383	9,383	
LA: Pool 3	1	1		204,913	45,081	
LA: Pool 4	1	1		1	1	
LA: Internal Sources	6,928	1		1	1	
LA: Local Tributaries	2,648	1,192		14,892	6,701	
WLA: Facilities	149	149		149	149	
WLA: MS4s	912	912		5,654	5,654	

Because the relationship of TSS and turbidity in the Lower Vermillion River that was used to determine attainment of the TMDL modeling goal was documented using a dataset that consists primarily of NTRU turbidity values, the two boundary condition loads that were iteratively reduced (internal sources and local tributaries) need to be adjusted upward to better represent load reductions that relate to a NTU goal (note that the Long Term Resource Monitoring Program (LTRMP) Hach 2100P has been correlated to their previously used Hach 16800, but not to the Metropolitan Council's (MCES) turbidity meter (Hach 2100A) used prior to 2006 – that which the MPCA has decided to use as the standard for turbidity assessment and TMDL work). Typically, TSS values that correspond to 20 NTRU are significantly less than those that correspond to 20 NTU values. For example, the Pool 3 (MCES-generated) data suggest a 20 NTU equivalent of approximately 60 mg/l TSS; the Upper Vermillion River (MCES-generated) data suggest a 20 NTU equivalent of approximately 80 mg/l, and the (LTRMP-generated) data at the mouth of the river (VM00.1M) suggest a 20 NTRU equivalent of approximately 25 mg/l. Thus, this adjustment results in a greater allowable load from internal sources and local tributaries.

The relationships between NTU values, NTRU values and TSS values vary geographically (as noted above, a TSS value that corresponds to 20 NTU is often double or more that which corresponds to 20 NTRU). To maintain a strong margin of safety, a conservative ratio of 1.50 (increase of 50 percent from NTRU-modeled reductions) was applied for the adjustment required to arrive at the final allocations for this TMDL. Note that this does not change the fundamental layout of the allocations or the basic requirements of this TMDL.

The final TMDL allocations are summarized in Table 6-2 and each of the various TMDL components are further discussed in subsequent chapters.

Table 6-2. TSS Allocation Summary for LVR Turbidity TMDL (adjusted to NTU).

Allocation Component: Source	Mode 0 (Minimal Pool 3 Inflow)			Mode 1 (Significant Pool 3 Inflow)		
	Existing TSS Load (kg/day)	Allowable TSS Load (kg/day)	Percent Reduction	Existing TSS Load (kg/day)	Allowable TSS Load (kg/day)	Percent Reduction
TMDL= LA+WLA+MOS	**12,117**	**7,793**	**36 percent**	**234,993**	**70,321**	**70 percent**
LA: UVR	1,478	1,478	0 percent	9,383	9,383	0 percent
LA: Pool 3	1	1	0 percent	204,913	45,081	78 percent
LA: Pool 4	1	1	0 percent	1	1	0 percent
LA: Internal Sources	6,928	3,464	50 percent	1	1	0 percent
LA: Local Tributaries	2,648	1,788	32 percent	14,892	10,052	33 percent
WLA: Facilities	149	149	0 percent	149	149	0 percent
WLA: MS4s	912	912	0 percent	5,654	5,654	0 percent
MOS (implicit)	(1) 20 percent based on running model to achieve 20 NTU instead of 25 NTU (2) Conservative value used to adjust from NTRU to NTU-based reduction requirements for local tributaries and internal sources.					

6.1.1 Wasteload Allocations

The WLAs for individual facilities and for Municipal Separate Storm Sewer Systems (MS4s) are provided in the following sections.

6.1.1.1 Individual Facilities

Table 6-3 identifies the facilities in the Vermillion River watershed with TSS limits in either their National Pollutant Discharge Elimination System (NPDES) or State Disposal System (SDS) permit. All of these facilities discharge upstream of the Vermillion River at Hastings and their loads therefore contribute to the load calculated for the Upper Vermillion River. The discharge from the Empire WWTP has been diverted to the Mississippi River, so the WLA for that facility (for discharge to the Vermillion River) will be zero. Since no other load reductions are specified for the Upper Vermillion River, this TMDL does not recommend any changes to the existing permits for the other facilities shown in Table 6-3. There are also a number of other permittees in the Upper Vermillion River, but most of them do not have any kind of water discharge or do not discharge TSS and do not require a WLA as part of this TMDL.

Loads from the numerous WWTPs and industrial facilities that discharge upstream of Mississippi River Pool 3 are accounted for in the load specified for Pool 3. Although the LVR TMDL recommends reductions from Pool 3, it was beyond the scope of this study to determine the specific manner in which this will occur. Therefore, if necessary, the permittees upstream of Pool 3 will receive individual WLAs as part of the Lake Pepin TMDL.

Table 6-3. List of NPDES and SDS facilities with TSS permit limits within the Vermillion River watershed and corresponding WLAs.

Facility Name	Permit Number	Design Flow (mgd)	TSS WLA and Limits
Elko/New Market WWTP	MN0056219	0.735	Calendar month average: 83.52 kg/day and 30 mg/L Max calendar week average: 125.19 kg/day and 45 mg/L
Intek Plastics Inc	MN0003417	0.200	Daily max: 14.4 kd/day and 19 mg/L
Met Council - Empire WWTP	MN0045845	Average wet weather: 14.4 Average annual: 12.0	0 (no longer discharges to LVR)
Vermillion WWTP	MN0025101	Average wet weather: 0.054	Calendar month average: 6.1 kg/day and 30 mg/L Max calendar week average: 9.2 kg/day and 45 mg/L

6.1.1.2 Municipal Separate Storm Sewer Systems

Under Phase II of EPA's NPDES stormwater program, rules have been developed to prevent harmful pollutants from being washed by stormwater runoff into MS4s (or from being dumped directly into the MS4) and then discharged into local waterbodies. The following cities and townships within the Vermillion River watershed fall under the Phase II guidelines (MPCA, 2007):

- City of Apple Valley
- City of Burnsville

- City of Hastings
- Empire Township
- City of Farmington
- City of Lakeville
- City of Rosemount

All of these entities are located upstream of the Vermillion River at Hastings and therefore their loads are included in the loads estimated for the Upper Vermillion River. Since no load reductions are specified for the Upper Vermillion River, this TMDL does not recommend any changes to the existing permits for the MS4 entities within the Vermillion River watershed. Despite this, Wasteload Allocations (WLA) were developed for the MS4s because their allowable discharge would have otherwise been assumed to be zero. The approach for developing the MS4 WLAs is described below:

1. The areal proportion of the Upper Vermillion River watershed that consists of MS4s was calculated at approximately 37.8 percent. This is based on the size of each MS4 as shown in Table 6-4 (total equals 105.4 square miles) and the drainage area of Upper Vermillion River (279 square miles).
2. Total MS4 WLAs for Mode 0 and Mode 1 were calculated by multiplying 37.8 percent by the allowable load for the Upper Vermillion River. Recall that the allowable load equals the existing load which is 2,413 kg/day during Mode 0 and 14,958 kg/day during Mode 1. The total MS4 WLA for Mode 0 is therefore 912 kg/day and for Mode 1 is 5,654 kg/day.
3. Several of the MS4s have had to complete Nondegradation Reports and the loads from those analyses were used to apportion the total MS4 WLAs to the individual communities. The results are presented in Table 6-4. Since Nondegradation Reports are not available for three of the communities, an average loading rate from the other three MS4s was applied.

Several important points should be noted regarding the approach for calculating the MS4 WLAs and the resulting values:

- The Nondegradation Reports have not yet been approved by MPCA and are therefore subject to change. This is one of the reasons the loads from the Nondegradation Reports were not independently used to calculate the WLAs.
- The allowable loads calculated for the Upper Vermillion River and shown in Table 6-2 are *delivered* loads which are a function of all the loads that enter the river upstream of the MCES monitoring station as well as in-stream processes such as deposition, re-suspension, etc. The delivered loads are therefore not directly comparable to the loads estimated for the Nondegradation Reports (which were not required to consider downstream fate and transport issues).
- The ultimate conclusion of the TMDL study is that load reductions are not needed for the Upper Vermillion River and therefore future loads from the MS4s should remain equal to or less than current levels, regardless of whether future modifications are made to the Nondegradation Report loads.

Table 6-4. WLAs that apply to the MS4s in the Upper Vermillion River Watershed.

MS4	Jurisdictional Area within UVR (sq mi)[a]	Proportion of UVR Watershed	Current TSS Load w/ BMPs (kg/yr)	Proportion of Total Annual Load	Mode 0 WLA (kg/day)	Mode 1 WLA (kg/day)
Apple Valley (MS400074)	15.35	5.5 percent	262,630[b]	8.2 percent	75	464
Burnsville (MS400076)	1.41	0.5 percent	39,717 [b]	1.2 percent	11	68
Lakeville (MS400099)	31.52	11.3 percent	1,279,400 [b]	39.8 percent	363	2,250
Farmington (MS400090)	11.63	4.2 percent	332,879 [c]	10.3 percent	94	582
Rosemount (MS400117)	3.30	1.2 percent	94,454 [c]	2.9 percent	26	164
Empire Township (MS400135)	34.34	12.3 percent	982,894 [c]	30.6 percent	279	1,730
Hastings (MS400240)	7.87	2.8 percent	225,259 [c]	7.0 percent	64	396
MnDOT Metro (MS400170)	Wasteload allocations for MNDOT and county roads are included in respective wasteload allocations for the municipalities that contain them.					
Dakota County (MS400132)						
Scott County (MS400154)						
Total	105.42	37.8 percent	3,217,232	100.0 percent	912	5,654

[a]Jurisdictional area is used as a surrogate for the MS4 area consistent with the approaches used for the Nondegradation Reports.
[b]Load available from Nondegradation Reports.
[c]Load estimated based on average areal load of three MS4s with Nondegradation Reports (equal to 28,622 kg/mi2/yr).

The Minnesota Department of Transportation (MN DOT) and Dakota County are also regulated under the Phase II program and are located within the watershed. The WLAs for these permittees are lumped in with the individual WLAs for each city/township based on the following:

- the loads were based on area, which would include the area of these MS4s;
- the loads are likely to be very small (less than one percent of the total load for each MS4); and
- the loads are difficult to quantify.

Table 6-5. MN DOT Permitted Roads in the Upper Vermillion River Watershed.

MN DOT Metro
TH 77
TH 61
TH 149
Interstate 35
Interstate 35E
TH 316
TH 291
TH 3
TH 55
TH 50
Interstate 494
TH 52

Various construction and industrial sites are also located in the watershed and fall under the Phase II guidelines. Similar to MnDOT and Dakota County, the WLAs for these permittees are lumped in with the individual WLAs for each city/township based on the following:

- Loads from construction stormwater are considered to be less than 1 percent of the total WLA and are difficult to quantify. Construction storm water activities are therefore considered in compliance with provisions of the TMDL if they obtain a Construction General Permit under the NPDES program and properly select, install and maintain all BMPs required under the permit, including any applicable additional BMPs required in Appendix A for discharges to impaired waters, or meet local construction stormwater requirements if they are more restrictive than requirements of the State General Permit.
- Loads from industrial stormwater are considered to be less than 1 percent of the total WLA and are difficult to quantify. Industrial storm water activities are considered in compliance with provisions of the TMDL if they obtain an industrial stormwater general permit or General Sand and Gravel general permit (MNG49) under the NPDES program and properly select, install and maintain all BMPs required under the permit.

6.1.2 Load Allocations

Load allocations are specified for anthropogenic sources that are not subject to NPDES permit requirements as well as "natural background" sources. For the LVR this includes non-permitted sources that contribute loads to the Upper Vermillion River, the local tributaries, Pool 3 and Pool 4, as well as activities that affect channel erosion and internal sources within the LVR. The load allocation expressed in Table 6-1 is simply the loading capacity that remains after the margin of safety and WLAs have been subtracted. Nonpoint sources to be targeted for the implementation of the TMDL include wind- and fish-induced re-suspension of fine sediments in the LVR lakes, the draining of wetlands in the system following the spring floods, channel erosion in the local tributaries, and upland erosion from agricultural activities in the LVR watershed. See Section 7.0 for more details.

6.1.3 Margin of Safety

The Clean Water Act requires that a TMDL include a margin of safety (MOS) to account for any lack of knowledge concerning the relationship between load and wasteload allocations and water quality. U.S. EPA guidance explains that the MOS may be implicit (i.e., incorporated into the TMDL through conservative assumptions in the analysis) or explicit (i.e., expressed in the TMDL as loadings set aside for the MOS).

An implicit MOS has been applied as part of the LVR by running the model to achieve a 30-day turbidity value of 20 NTUs instead of 25 NTUs. A relatively large MOS is specified because of the considerable uncertainty associated with understanding and modeling a system as complex as the LVR. Examples of the complexity are presented below:

- The SWAT model of the local tributaries could not be calibrated due to a lack of sampling data within the tributaries.
- The LVR system is hydrologically complex with flow entering the system from the Upper Vermillion at Hastings, via local tributaries, through movement of groundwater; and by interflow with the Mississippi.
- Sediment re-suspension due to fish activity and the phenomenon of storage and release of solids load in wetland areas are not readily handled in the W2 model.

6.2 Critical Conditions and Seasonality

The Clean Water Act requires that TMDLs take into account critical conditions for stream flow, loading, and water quality parameters as part of the analysis of loading capacity. The critical conditions (the periods when the greatest reductions are required) were inherently addressed through the use of continuous modeling over a twelve-year period and by identifying load reductions that will achieve water quality standards. The final TMDL is therefore based on a scenario that results in meeting water quality standards at all locations during all seasons. Mode 0 (significant Pool 3 inflow) is a somewhat more critical condition in that larger load reductions (72 percent) are needed compared to Mode 1 (69 percent) (Table 6-1).

7.0 GENERAL IMPLEMENTATION STRATEGY

Implementation of the LVR TMDL will require efforts in a number of fronts. First, this analysis has demonstrated that during much of the year Pool 3 has a significant impact on water quality in the LVR and it is therefore unreasonable to expect that water quality standards can be met in the LVR without first improving water quality in Pool 3. Initial efforts to do so are underway through the development of the Lake Pepin TMDL, which is expected to be completed by 2009. It is anticipated that many sources will need to be controlled over a long period of time to implement the Lake Pepin TMDL since the upstream watershed area is so large (approximately 48,634 square miles).

Secondly, during other periods of the year, water quality in the LVR has been demonstrated to be impacted by a variety of internal sources that might include wind-induced re-suspension of fine sediments, fish-induced re-suspension, and the draining of wetlands in the system following spring floods. Although it might be challenging to address these sources, it is unlikely that water quality standards can be met if they are not controlled. Section 7.1 offers some preliminary ideas for doing so.

Finally, the impact of the local tributaries on the LVR is still not fully understood. Although the modeling suggests that they are not a significant cause of the turbidity problem, there is still some uncertainty associated with this finding and the TMDL therefore recommends a 55 percent load reduction as part of the MOS. There are a variety of practices that could potentially achieve this load reduction, some of which are described in Section 7.1.

7.1 Potential Implementation Activities

This section of the report focuses on various potential activities that could reduce sediment loads from internal sources and the local tributaries to the LVR.

7.1.1 Water Level Management

Prior to 1866, the Upper Mississippi River was a free-flowing river comprised of a mosaic of channels, sand bars, and wooded islands. When the system of locks and dams was completed in the 1930s, the free flowing river had been transformed into a series of navigation pools and the high water levels made the islands in the lower portion of the pools more vulnerable to erosion from waves. Aquatic plants that grew in the shallow water bordering the islands were affected by these changes, and many formerly lush plant beds either decreased in size or disappeared completely (River Resources Forum Water Level Management Task Force, 2007). These aquatic plants served an important role in reducing waves, stabilizing bottom sediments, and capturing sediment.

To try and restore the historic levels of aquatic vegetation, water level management in the Upper Mississippi River has been ongoing since the early 1990's and offers a way to help restore the natural seasonal fluctuation in water levels that the plants desire. A recent report (River Resources Forum Water Level Management Task Force, 2007) suggests that water level management might have a positive benefit on water clarity, although additional research is needed. Figure 7-1 indicates that there are significant areas of potential future aquatic vegetation beds in the vicinity of the LVR.

MDNR has identified three water level management strategies that could be used in the LVR:

1. Pool-wide Pool 4 summer drawdowns.
2. Vermillion Bottoms/Goose Lake HREP type drawdowns of the LVR.
3. Individual LVR backwater lake drawdowns.

The effectiveness, expense and ease of implementation will vary widely for each strategy and should be explored as part of the implementation of this TMDL.

Although water level management offers great promise for improving water quality in the Upper Mississippi River, the following issues should be considered with regard to potential impacts on turbidity conditions in the LVR:

- Because the water level management drawdowns typically start after the Spring flood, drawdowns in Pool 3 should have only a minor impact on the frequency of intrusion into the LVR. Drawdowns in Pool 4 would lower the summer base level of the LVR and decrease backwater effects into the LVR. This could increase velocities in the LVR and also increase the amount of swamp drainage, both of which could increase turbidity for a short time during this period.

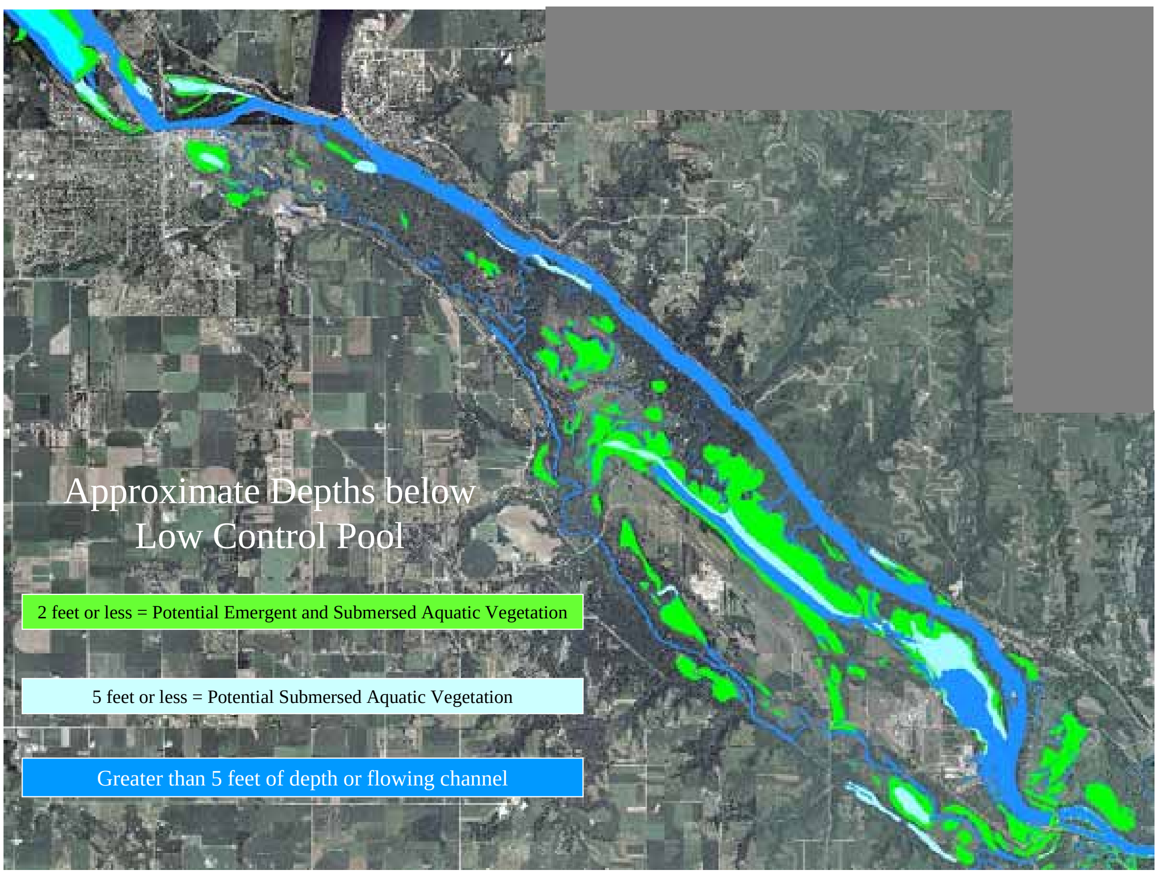

Figure 7-1. Potential Aquatic Vegetation Beds in Pool 3 and the LVR. (Courtesy of MDNR).

7.1.2 Fish Management

Although rough fish have been identified as a potential source of the high turbidity in the LVR, any attempt to actively remove rough fish from the system would be ongoing, expensive and unlikely to succeed (MDNR, 2008). DNR believes it may be possible to induce rough fish to leave and largely stay out of backwater lakes following the spring flood pulse if the rough fish sense they will be trapped by lowering water levels. Any rough fish control ideas to implement the TMDL should be implemented using an adaptive management approach (i.e., conduct initial projects as experiments or pilot efforts and implement future efforts based on the success (or failure)) of the initial efforts).

7.1.3 Agricultural Best Management Practices

Sediment is typically exported from agricultural fields by overland flow with the magnitude of the load depending on field topography, soil compaction, surface roughness, and use of best management practices (BMPs). Several structural and non-structural BMPs described below have been developed and studied for use in agricultural areas. Though the BMPs are presented individually, they typically must be used in combinations to mitigate hydrologic and water quality impacts.

Some BMPs will be effective on all farms, regardless of drainage patterns. Others are only applicable to certain fields. It will be up to the individual operator to determine the BMPs best suited for his or her operation.

7.1.3.1 Tillage Practices

Several practices are commonly used to maintain a suggested 30 percent cover:

- No-till systems disturb only a small row of soil during planting, and typically use a drill or knife to plant seeds below the soil surface.
- Strip till operations leave the areas between rows undisturbed, but remove residual cover above the seed to allow for proper moisture and temperature conditions for seed germination.
- Ridge till systems leave the soil undisturbed between harvest and planting: cultivation during the growing season is used to form ridges around growing plants. During or prior to the next planting, the top half to two inches of soil, residuals, and weed seeds are removed, leaving a relatively moist seed bed.
- Mulch till systems are any practice that results in at least 30 percent residual surface cover, excluding no-till and ridge till systems.

Corn residues are more durable and capable of sustaining the required 30 percent cover required for conservation tillage. Soybeans generate less residue, the residue degrades more quickly, and supplemental measures or special care may be necessary to meet the 30 percent cover requirement (UME, 1996). Figure 7-2 shows a comparison of ground cover under conventional and conservation tillage practices.

Figure 7-2. Comparison of conventional (left) and conservation (right) tillage practices.

7.1.3.2 Cover Crop

Grasses and legumes may be used as winter cover crops to reduce soil erosion and improve soil quality. These crops also contribute nitrogen to the following crop. Grasses tend to have low seed costs and establish relatively quickly, but can impede cash crop development by drying out the soil surface or releasing chemicals during decomposition that may inhibit the growth of a following cash crop. Legumes take longer to establish, but are capable of fixing nitrogen from the atmosphere, thus reducing nitrogen fertilization required for the next cash crop. Legumes, however, are more susceptible to harsh winter environments and may not have adequate survival to offer sufficient erosion protection. Planting the cash crop in wet soil that is covered by heavy surface residue from the cover crop may impede emergence by prolonging wet, cool soil conditions. Cover crops should be killed off two or three weeks prior to planting the cash crop either by application of herbicide or mowing and incorporation, depending on the tillage practices used.

Cover crops alone may reduce soil and runoff losses by 50 percent, and when used with no-till systems may reduce soil loss by more than 90 percent (IAH, 2002). Use of cover crops is illustrated in Figure 7-3.

(Photo Courtesy of CCSWCD)

Figure 7-3. Use of Cover Crops.

The NRCS provides additional information on cover crops at:
http://efotg.nrcs.usda.gov/references/public/IL/340.pdf

7.1.3.3 Vegetative Controls

Other control measures for agricultural land use include vegetated filter strips, grassed waterways, and riparian buffers. Filter strips are used in agricultural and urban areas to intercept and treat runoff before it leaves the site. If topography allows, filter strips may also be used to treat effluent from tile drain outlets.

Filter strips will require maintenance, including grading and seeding, to ensure distributed flow across the filter and protection from erosion. Periodic removal of vegetation will encourage plant growth and uptake and remove nutrients stored in the plant material. Filter strips are most effective on sites with mild slopes of generally less than 5 percent, and to prevent concentrated flow, the upstream edge of a filter strip should follow one elevation contour (NCDNR, 2005). A grass filter strip is shown in Figure 7-4.

(Photo Courtesy of CCSWCD)

Figure 7-4. Grass Filter Strip Protecting Stream from Adjacent Agriculture.

7.1.3.4 Riparian Buffers

Preserving natural vegetation along stream corridors can effectively reduce water quality degradation associated with adjacent land disturbance. The root structure of the vegetation in a buffer enhances infiltration of runoff and subsequent trapping of nonpoint source pollutants. Tree canopies of riparian forests also cool the water in streams which can affect the composition of the fish species in the stream, as well as the rate of biological reactions.

Even more important than the filtering and cooling capacity of the buffers is the protection they provide to streambanks. The rooting systems of the vegetation serve as reinforcements in streambank soils, which helps to hold streambank material in place and minimize erosion. Due to the increase in stormwater runoff volume and peak rates of runoff associated with agriculture and development, stream channels are subject to greater erosional forces during stormflow events. Thus, preserving natural vegetation along stream channels minimizes the potential for water quality and habitat degradation due to streambank erosion and enhances the pollutant removal of sheet flow runoff from developed areas that passes through the buffer.

Riparian buffers should consist of native species and may include grasses, grass-like plants, forbs, shrubs, and trees. Minimum buffer widths of 25 feet are required for water quality benefits. Higher removal rates are provided with greater buffer widths. Riparian corridors typically treat a maximum of 300 ft of adjacent land before runoff forms small channels that short circuit treatment. Buffer widths based on slope measurements and recommended plant species should conform to NRCS Field Office Technical Guidelines. A riparian buffer protecting the stream corridor from adjacent agricultural areas is shown in Figure 7-5.

There are also a number of significant gullies that are washing within the LVR that could be addressed using Grade Stabilization Structures (Dakota County SWCD, 2008). MDNR also advocates for the use of riparian buffers containing permanent vegetation along all gulleys, ravines and valleys in the lower watersheds (MDNR, 2008).

(Photo Courtesy of CCSWCD)

Figure 7-5. Riparian Buffer Between Stream Channel and Agricultural Areas.

7.1.4 Urban Best Management Practices

A small portion of the LVR watershed (8 percent) is classified as medium density residential. Relative to row crop agriculture, urban land uses typically have more vegetative cover on pervious surfaces (e.g., lawns, parks, etc.), so sediment loading is often less. During construction, however, sediment loading can exceed that of row crop agriculture and increases in the amount of impervious surface through the construction of roads, parking lots, and building footprints significantly alters site hydrology by decreasing infiltration, increasing surface runoff, and decreasing travel times such that peak and total flow volumes are substantially increased. The altered hydrology can also impact stream morphology, leading to unstable streams, bank and channel erosion, siltation, habitat modification, etc. Urbanization also tends to lead to a loss of riparian corridor vegetation, which can increase stream temperatures, reduce filtering capacity, and destabilize streambank soils.

Watershed management and the protection of water quality in urban areas require a combination of strategies, generally grouped as regulatory and non-regulatory options. Regulatory options are those that involve government action and include approaches such as zoning and subdivision and construction regulations. Nonregulatory options may involve government action, but not in the form of a development regulation. For example local governments or other organizations may acquire land, conduct monitoring, and encourage better site design using low impact development or conservation design principles, and educate homeowners about good stewardship and good housekeeping practices.

Both regulatory and non-regulatory options rely on a variety of structural BMPs to control stormwater from urban areas. Structural practices require construction, installation, and maintenance. The types of practices recommended for a given area depend on several factors including watershed characteristics, physical site constraints, maintenance requirements, administrative resources, and cost. The following is a list of commonly used structural BMPs and the Minnesota Stormwater Manual (http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html) provides information on the design and reported effectiveness of each BMP:

- Bioretention Cell
- Rainwater Harvesting
- Conventional Dry Detention
- Extended Dry Detention
- Grass Swale
- Green Roof
- Infiltration Trench
- Water Quality Swale
- Underground Storage
- Permeable Pavement
- Sand Filter
- Stormwater Wetland
- Vegetated Filter Strip
- Wet Pond

7.2 Future Monitoring

A detailed monitoring plan will be developed as part of the implementation planning process that will follow completion of this TMDL. Future monitoring must focus on (1) documenting changes in water quality, (2) understanding effectiveness of various best management practices on the land and (3) evaluating water level management exercises and decisions. It is important to note that the monitoring plan designed for the Lake Pepin TMDL will be applicable to the LVR TMDL; in particular, understanding water quality changes in Mississippi River Pool 3 will be important. The core components of the LVR TMDL monitoring plan should include:

(1) Monitor loads at stations VR2.0 (METC station in Hastings) and VM00.1M (USGS station at mouth) to assess progress towards meeting water quality standards. At this time, sampling at both of these sites and gauging at the VR2.0 site is on-going and fully funded.

(2) Utilize continuous turbidity monitoring to better understand the dynamics of the Lower Vermillion River system. The Dakota County Soil and Water Conservation District was contracted in 2008 to deploy and maintain three turbidity probes in the LVR; the goal is to continue this monitoring indefinitely.
(3) Additional sampling within the LVR to better characterize and target controls for internal sources such as wind-induced re-suspension of fine sediments, fish-induced re-suspension, boat-induced re-suspension, and the draining of wetlands in the system following spring floods. This monitoring is not yet in place, and will require detailed planning.
(4) Monitoring of the local tributaries (those that drain directly to the system from the west) to the LVR to understand their impact during different flow and seasonal conditions.
(5) Monitoring to determine the effectiveness of any BMPs that are implemented as a result of the TMDL. This need is common to most water quality improvement projects, and there is significant funding for research and monitoring that will be useful to the LVR TMDL and implementation planning. Further work specific to the LVR watershed would be beneficial.

8.0 PUBLIC PARTICIPATION RECORD

Public participation is an important and required component of the TMDL development process. A "kickoff" public meeting for this project was held February 26, 2004 at the Hastings City Hall and another meeting was held November 30, 2006 in Farmington to present the results of Phases I and II of the study. A final public meeting was held on March 19, 2008 at the Pleasant Hill Library in Hastings to present the draft TMDL report and MPCA also will accept written comments on the draft report for a period of 30 days.

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REFERENCES

Cole, T.M., and S. A. Wells. 2003. *CE-QUAL-W2: A two-dimensional, laterally averaged, Hydrodynamic. and Water Quality Model, Version 3.2*. Instruction Report EL-03-1, US Army Engineering and Research Development Center, Vicksburg, MS.

Dakota County Soil and Water Conservation District (SWCD). 2008. Comments on Agency Review Draft of Lower Vermillion River TMDL Phase III Report. Submitted February 7, 2008.

Dieterman, D. 2002. Major River Survey, Upper Mississippi River Pools 3, 5, 5A, 6, 7, upper 9, and LVR. Minnesota Department of Natural Resources. Lake City, MN.

Hoffman, R., and K. Kearns, eds. 1997. *Wisconsin Manual of Control Recommendations for Ecologically Invasive Plants*. Wisconsin Department of Natural Resources, Madison, WI.

IAH (Illinois Agronomy Handbook). 2002. Illinois Agronomy Handbook, 23rd Edition. University of Illinois Extension, College of Agricultural, Consumer, and Environmental Sciences.

MDNR (Minnesota Department of Natural Resources). 2008. Comments on Agency Review Draft of Lower Vermillion River TMDL Phase III Report. Submitted by Scot Johnson, DNR Waters. February 7, 2008.

MPCA (Minnesota Pollution Control Agency). 2007. Minnesota's Mandatory Small MS4s Updated March 22, 2007. Accessed online at: ***http://www.pca.state.mn.us/publications/wq-strm4-74.pdf*** on October 29, 2007.

NCDNR (North Carolina Department of Environment and Natural Resources). 2005. Updated Draft Manual of Stormwater Best Management Practices. North Carolina Department of Environment and Natural Resources, Division of Water Quality.

Newcombe, C.P., and J.O.T. Jensen. 1996. Channel suspended sediment and fisheries: A synthesis for quantitative assessment of risk and impact. *N. Am. J. Fish. Manage.* 16:693–627.

Parkos, J.J. V. J. Santucci, Jr. and D. H. Wahl. 2003. Effects of adult common carp (*Cyprinus carpio*) on multiple trophic levels in shallow mesocosms. *Can. J. Fish. Aquatic Sci*. 60: 182-192.

River Resources Forum Water Level Management Task Force. 2007. Summary of Results of the Pool 5 and Pool 8 Drawdownson the Upper Mississippi River. July 2007.

UME (University of Minnesota Extension). 1996. Tillage Best Management Practices for Corn-Soybean Rotations in the Minnesota River Basin, University of Minnesota Extension, FO-06676.

UMRCC (Upper Mississippi River Conservation Committee-Water Quality Technical Section). 2003. Proposed water quality criteria necessary to sustain submersed aquatic vegetation in the Upper Mississippi River. Upper Mississippi River Conservation Committee.

UMRSEMP (Upper Mississippi River System Environmental Management Program). 1990. Goose Lake Water Level Control Habitat Rehabilitation and Enhancement Project, Pool 3, Upper Mississippi River, Dakota and Goodhue Counties, Minnesota. Upper Mississippi River System Environmental Management Program, Definite Project Report/Environmental Assessment (SP-6). U.S. Army Corps of Engineers, St. Paul District.

USEPA (U.S. Environmental Protection Agency). 2006. Memorandum on Establishing TMDL "Daily" Loads in Light of the Decision by the U.S. Court of Appeals for the D.C. Circuit in *Friends of the Earth, Inc. v. EPA*, et al., No.05-5015, (April 25, 2006) and Implications for NPDES Permits - Benjamin H. Grumbles. November 15, 2006.

Walker, W.W., Jr. 1987. Empirical Methods for Predicting Eutrophication in Impoundments, Report 4, Phase III: Applications Manual. Technical Report E-81-9. U.S. Army Corps of Engineers, Washington, DC.

APPENDIX A: PHASE I REPORT

APPENDIX B: MODELING REPORT

APPENDIX C: METHODOLOGY FOR CREATING FUTURE TIME SERIES FOR UPPER VERMILLION RIVER

Appendix A

Lower Vermillion River Watershed Turbidity TMDL Project

Phase I Report: Data Gathering and Conceptual Model Development

April 23, 2004

Submitted to:
Minnesota Pollution Control Agency

Submitted by:
Tetra Tech, Inc.

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TABLES

FIGURES

EXECUTIVE SUMMARY

The Vermillion River from Hastings to the confluence with the Mississippi River, referred to as the Lower Vermillion River (LVR), is included on Minnesota's Clean Water Act Section 303(d) list of impaired waters for turbidity. Water quality monitoring of the LVR has shown that its turbidity levels frequently exceed the Minnesota Pollution Control Agency's (MPCA) criterion of 25 Nephelometric Turbidity Units (NTU). As required by the Clean Water Act, MPCA has recently initiated development of a total maximum daily load (TMDL) to address the turbidity impairment. The purpose of developing a TMDL is to identify the pollutant loading that a waterbody can receive and still achieve water quality standards.

Turbidity is a measure of water clarity. When turbidity is elevated, the water appears cloudy and visibility is reduced. In addition to being unaesthetic, elevated turbidity has adverse impacts on aquatic life. For example, elevated turbidity reduces the ability of sight-feeding gamefish to find their prey and reduces the vigor of the submerged aquatic vegetation that forms the basis of a healthy ecosystem in most Minnesota rivers. Elevated turbidity can be caused by a number of factors, including loads of fine sediment, growth of microscopic floating algae exacerbated by nutrient loads, and dissolved organic material.

The goals of the LVR Watershed Turbidity TMDL Project are to describe the nature and extent of turbidity in the highly complicated setting of the LVR; determine the linkage between turbidity and sediment and nutrient loading sources; and produce a final report that expresses potential solutions to the turbidity problem in terms of an "allocation" among sources and recommendations for corrective actions. Due to the complexities of the system, the project is being implemented in three phases. This report documents the results of the Phase I analysis: Data Gathering and Conceptual Model Development.

The LVR receives flow, and associated pollutant loads, from four sources: flow from the Upper Vermillion River (upstream of Hastings), inflow from the Mississippi River, flow from small local tributaries to the LVR, and groundwater. It is the inflow from the Mississippi that renders analysis of the LVR particularly complex.

Modifications of the hydrologic regime of the Vermillion River Bottoms have had significant impacts on the suspended solids load and the associated turbidity of the LVR. The most notable change is associated with the impoundment of Mississippi Pool 3, beginning in 1936, which raised the stage of the Mississippi and created a tendency for water to flow from the Mississippi into the LVR. Historical data were assessed to determine the extent of the modifications and their potential effects on the suspended solids load and turbidity. A review of historic aerial photos indicates that the hydrology of this area was very dynamic and complex even prior to the creation of Mississippi Pool 3. Anthropogenic impacts, in the form of roads, hydrologic modifications, and agricultural use, were already apparent in the LVR in the late 1930s and these impacts were further compounded by the creation of Pool 3. Historic discharge data were evaluated and indicate that the magnitude and duration of annual flow extremes in the Mississippi River changed significantly from pre-dam to post-dam conditions, with minimum flows decreasing and maximum flows significantly increasing.

Recent water quality and biological monitoring data were obtained during Phase I from a number of agencies, including MPCA, the Minnesota Department of Natural Resources, the U.S. Geological Survey, the Metropolitan Council of Environmental Services (MCES), the U.S. Army Corps of Engineers, the Wisconsin Department of Natural Resources, and the Prairie Island Indian Community. All of these data were compiled into one master database and analyzed. The available data confirm the turbidity impairment in the LVR and indicate that turbidity typically increases from March through September. Forty percent (162 of 414) of all samples exceeded the 25 NTU numeric criterion at the mouth of the

LVR during the period January 24, 1990 to September 18, 2002. Significant increases in turbidity are also observed moving downstream in the LVR from Hastings to its mouth.

Insufficient data were identified with which to fully characterize the current health or trends of the LVR aquatic communities. However, the data do suggest that the LVR and its associated lakes are supporting fair populations of game fish species. Also, there appear to be some pieces of excellent aquatic life habitat within a system that is poor overall. However, although some fish species seem in good health, qualitative evidence suggests that high turbidity levels might be affecting other species in the LVR. Local residents report that water clarity used to be much better and aquatic vegetation more abundant. Furthermore, anglers in the area reported catching fair amounts of yellow perch in the past and perch are now found only in very small numbers in the Vermillion system. Research has shown that yellow perch are more susceptible to negative effects from turbidity and sedimentation than some other game-fish species (Newcomb et al., 1996).

Flow from the Mississippi frequently enters the LVR because the water surface elevation maintained for navigation in Pool 3 is typically 5 or 6 feet higher than the water surface elevation in the LVR. Considerable effort was expended during Phase I activities to identify and confirm information related to the numerous manmade structures that control the interchange of water between the LVR and Pool 3. This interchange depends on the relative stage in the two systems. At a gross conceptual level, four modes of behavior can be distinguished: Normal Flow (Mode 1), Mississippi High Flow (Mode 2), Upper Vermillion High Flow (Mode 3), and Cannon River Flood (Mode 4). Stage in Pool 3 is low enough to prevent flow from the Mississippi to the LVR about 50 percent of the time (Mode 1). Above this level, flow can enter the LVR from Pool 3, first via Vermillion Slough, then via Truedale and Carter Slough (Mode 2). High water in the Upper Vermillion (Mode 3) may cause a reversal of flow through the Vermillion Slough. Finally, elevated stage below Lock and Dam 3, or flood flows in the Cannon River, can cause a backwater with reversal of flow into the downstream end of the LVR (Mode 4).

Sufficient data are not yet available to complete a quantitative analysis of flow between the LVR and Mississippi, and this will be a focus of Phase 2 activities. However, an order of magnitude estimate can be made using preliminary stage-discharge estimates for the sloughs. In sum, on a long-term basis the LVR system appears to receive significantly more inflow from Mississippi Pool 3 than from the Upper Vermillion. Even when estimates of inflow from local tributaries to the LVR and groundwater discharge (probably on the order of 100 cfs) are added, the long-term inflow from Pool 3 is still more than twice the flow from other sources. Cumulative loading to the LVR (of water and pollutants) thus depends largely on the Mississippi. However, during low to moderate flow conditions, inflow to the LVR can be dominated by its own watershed.

Inflow from the Mississippi brings into the LVR pollutants that may originate throughout the upstream watershed, including the Minnesota River, which is an important source of both sediment and nutrient load. In general, solids concentrations in Mississippi Pool 3 are similar to those in the Upper Vermillion, while phosphorus concentrations are lower (due largely to the presence of the Empire WWTP on the Upper Vermillion). However, the loading from the Mississippi is likely to dominate total loads, because the total flow contribution is higher. The inflows can occur as large events, with significant erosive energy that can generate sediment load from the channel and banks of the LVR. In addition, material that is washed into the many lakes of the LVR may be later remobilized by the action of wind and waves.

The relationships between turbidity, TSS, and chlorophyll *a* were explored to begin to understand the causes of elevated turbidity in the LVR. Although more data are needed, the following tentative inferences can be made:

- Inorganic sediment appears to be the primary cause of elevated turbidity. Sources of inorganic sediment include the Mississippi River, the Upper Vermillion River, channel erosion, and local tributaries.
- Pathways involving algae and organic detritus contribute about 38 percent (on average) of the observed turbidity in the LVR.
- Volatile solids (algae and organic detritus) do not appear to be a major component of turbidity in Mississippi Pool 3, which is controlled by the suspended sediment load. External loads of algae and detritus to the LVR are likely not significant contributors to the turbidity problem.
- Algal growth within the LVR is a secondary contributor to turbidity and is sensitive to concentrations of phosphorus. Therefore, an analysis of phosphorus input to the system will also be useful.

Based on these findings, the primary need for more fully evaluating the turbidity problem in the LVR is the creation of a model to provide a more complete description of the movement of water in the system and to link sediment sources with turbidity impacts. A secondary need is the creation of a model to evaluate the impact of nutrients and algae. Three alternative approaches are presented for modeling. The first two approaches are generally consistent with the concepts, schedule, data collection efforts, and approximate budget described in the Statement of Work. The third approach is a more rigorous and complex modeling effort that would require additional time and budget to complete. Use of the third approach would provide a stronger scientific and technical basis for completing the project. However, from a practical point of view, the simpler approaches may be adequate to address the pertinent questions related to the sources and nature of the turbidity impairment.

Based on additional discussions with MPCA and comments received on the draft Phase I report, we are recommending our Middle Approach: Integrated Hydrologic/Water Quality CE-QUAL-W2 Modeling. This middle approach is recommended for the following reasons:

- Consistent with existing schedule and budget
- CE-QUAL-W2 will predict increased light availability due to a decrease in TSS/sediment
- Should result in a better calibration than the simple approach
- Will meet the regulatory needs of the TMDL
- Does not require separation of the hydrodynamic and water quality modeling
- Provides the advantage of using a tested and widely accepted model – although some code modification will likely still be needed.

1 INTRODUCTION

The Vermillion River from Hastings, Minnesota, to the confluence with the Mississippi River, referred to as the Lower Vermillion River (LVR), is included on Minnesota's Clean Water Act Section 303(d) list of impaired waters because of turbidity (Figure 1-1). Water quality monitoring of the LVR has shown that its turbidity levels frequently exceed the Minnesota Pollution Control Agency's (MPCA) standard of 25 nephelometric turbidity units (NTU). As required by the Clean Water Act, MPCA has recently initiated development of a total maximum daily load (TMDL) to address the turbidity impairment. The purpose of developing a TMDL is to identify the pollutant loading that a waterbody can receive and still achieve water quality standards. The TMDL process identifies the maximum allowable load; allocates portions of the maximum load to all sources; identifies the necessary controls, which may be implemented voluntarily or through regulatory means; and describes a monitoring plan and associated corrective feedback loop to ensure that the uses or the waterbody are fully supported.

Turbidity is a measure of water clarity. When turbidity is elevated, the water appears cloudy and visibility is reduced. In addition to being unaesthetic, elevated turbidity has adverse impacts on aquatic life. For example, elevated turbidity reduces the ability of sight-feeding gamefish to find their prey and reduces the vigor of the submerged aquatic vegetation that forms the basis of a healthy ecosystem in most Minnesota rivers. Elevated turbidity can be caused by a number of factors, including loads of fine sediment, growth of microscopic floating algae exacerbated by nutrient loads, and dissolved organic material.

The goals of the LVR Watershed Turbidity TMDL Project are to describe the nature and extent of turbidity in the highly complicated setting of the LVR, determine turbidity source load allocations that consider major sediment and nutrient sources, and produce a final report that expresses the complicated turbidity dynamics in terms of an "allocation" among sources and recommendations for corrective actions. Because of the complexities of the system, the project is being implemented in three phases:

- Phase I: Data Gathering and Conceptual Model Development
- Phase II: Sampling and Model Development
- Phase III: Model Refinement and TMDL Development

This report documents the results of the Phase I analysis.

1.1 Document Purpose and Content

The purposes of this document are to summarize the available data related to turbidity conditions in the LVR, to develop an understanding of the multiple factors that affect turbidity, and to present a conceptual model for hydrologic and pollutant mass balances. Section 2 of the document describes the current and historical condition of the Vermillion River watershed and Section 3 summarizes the available water quality and biological data. Section 4 describes conceptual models for hydrology, sediment, and phosphorus for the LVR and presents preliminary conclusions regarding the most significant factors affecting turbidity. Section 5 offers recommendations for additional monitoring and modeling.

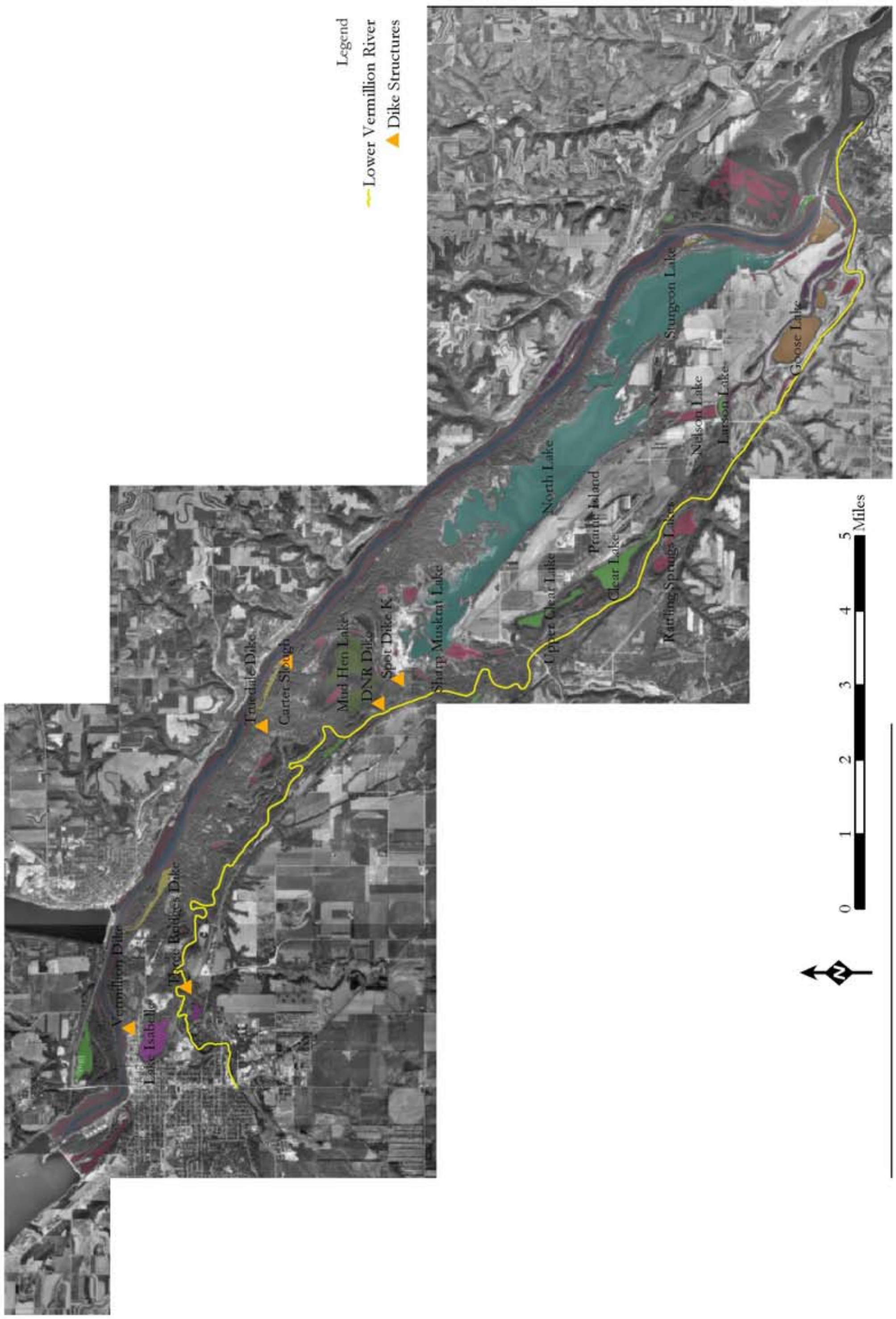


Figure 1-1. The Lower Vermillion River.

1.2 Future Phases

This report concludes Phase I of the project. Monitoring and modeling will be conducted during Phase II to fill the identified data gaps and to more fully quantify the turbidity impairment. Phase III will involve an assessment of the data collected during Phase II, completion of the modeling, and preparation of the final TMDL report. The tentative schedule for Phases II and III is shown in Table 1-1.

Table 1-1. Tentative Schedule for LVR Watershed Turbidity TMDL Project

Phase	Deliverable	Date
I	Kickoff Technical Advisory Committee Meeting	January 2004
I	Kickoff Public Meeting	February 2004
I	Second Technical Advisory Committee Meeting	March 2004
I	Phase I Report	April 2004
II	Monitoring Activities	Spring/Summer/Fall 2004
II	Development of Model(s)	Spring/Summer/Fall 2004
II	Model Calibration Report	December 2004
II	Phase II Progress Report	December 2004
II	Phase II Progress Report Meeting	December 2004
III	Draft TMDL Report	June 2005
III	TMDL Public Meeting	July 2005
III	Final TMDL report	August 2005

2 DESCRIPTION OF THE WATERSHED

2.1 Current Conditions

The Vermillion River travels approximately 59 miles from its headwaters in southeastern Scott County near New Market to the confluence with the Mississippi River south of Lock and Dam 3. The watershed drains about 356 square miles and consists of 17 subwatersheds (Figure 2-1).

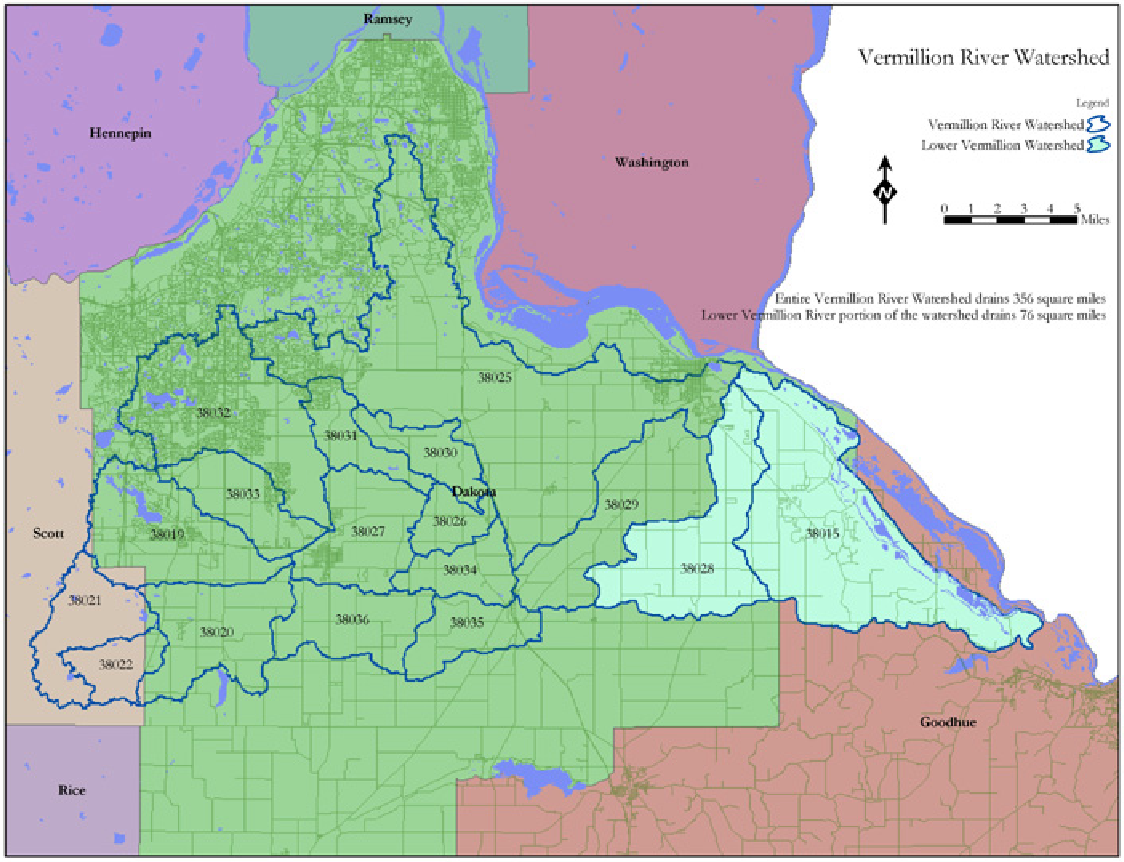
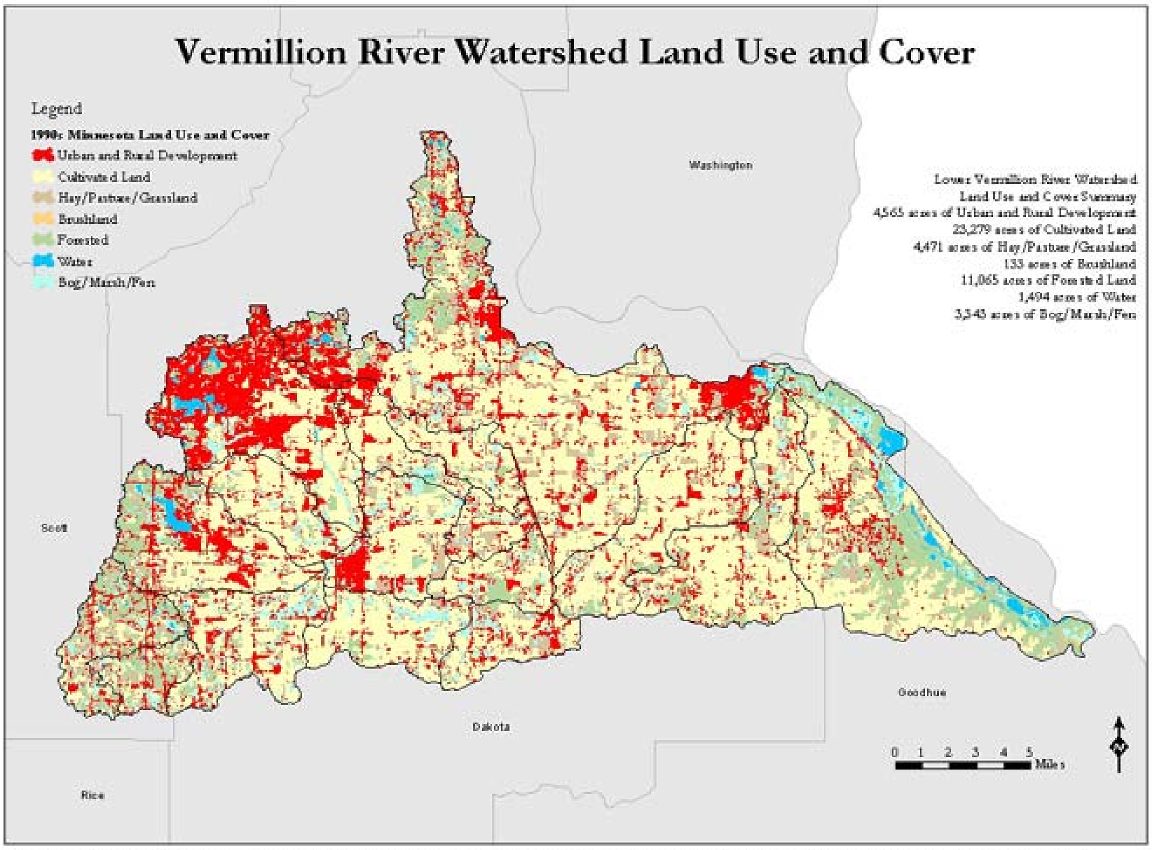


Figure 2-1. Vermillion River watershed boundaries.

Land use and land cover for the Vermillion River watershed (Figure 2-2) consist of 49 percent cultivated land; 20 percent urban and rural development; 12 percent forested land; 11 percent hay, pasture, and grassland; 7 percent bog, marsh, and fen; and 1 percent water (MNDNR, 1990).



Map adapted from data obtained from MN Department of Natural Resources (Minnesota Land Use and Cover: 1990s Census of the Land, Watershed Boundaries, and County Boundaries).

Figure 2-2. Vermillion River Watershed Land Use and Cover

Below the Old Peavey Mill Dam in Hastings, the Vermillion River splits. One branch (Vermillion Slough) flows to the north to join the Mississippi River near mile 813, and the other branch drops approximately 90 feet to join the floodplain of the Mississippi River. The floodplain of the LVR and Mississippi River is known as the Vermillion River Bottoms. On this alluvial floodplain, the Lower Vermillion River parallels the Mississippi River for approximately 20 miles before joining it just downstream from Lock and Dam 3 near Red Wing, Minnesota. The Lower Vermillion watershed consists of two subwatersheds draining approximately 76 square miles (Figure 2-1).

Land use and land cover for the LVR watershed (Figure 2-2) consist of 48 percent cultivated land; 9 percent urban and rural development; 23 percent forested land; 9 percent hay, pasture, and grassland; 7 percent bog, marsh, and fen; and 3 percent water (MNDNR, 1990).

The Vermillion River is connected to the Mississippi River from Hastings to approximately river mile 807 by a series of sloughs and low areas that make up the Gores Wildlife Management Area (USACE, 1988). Under high-flow conditions, discharge into the Vermillion River Bottoms from the Mississippi River main channel can occur through as many as 22 individual inlets or low spots (Scot Johnson, MNDNR Waters, office memorandum January 4, 1996). During periods of high flow, the Mississippi River is permitted to flow through several inlets that separate the two rivers. The most notable are the Vermillion Slough, the Truedale Slough, and the Carter Slough, which consist of six dike structures (Figure 2-3). Table 2-1 summarizes the information gathered to date on these inlets. Additional detailed information on these inlets is presented in Section4.

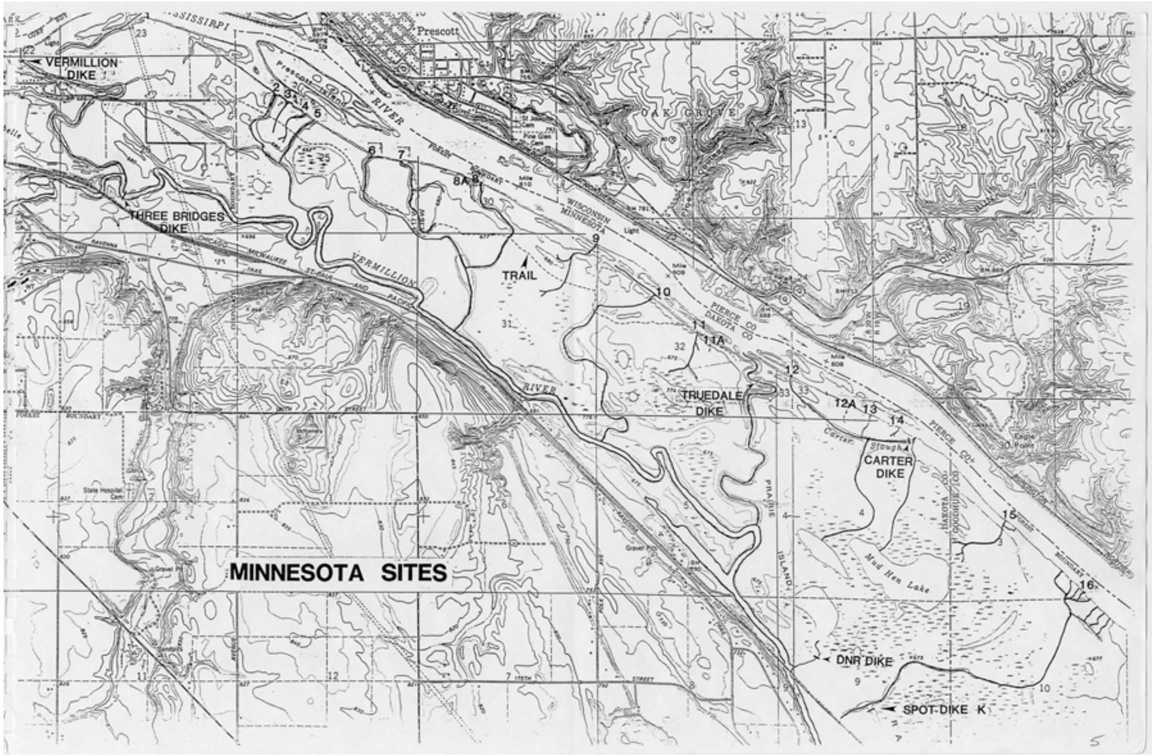


Figure 2-3. Minnesota sites (USACE, 1987).

Table 2-1. Structure Specifications

Inlet Name	Structure	Date Constructed	Description	Elevation[1] (NGVD 1929)	Approximate River Mile
Vermillion Slough	Vermillion Slough Dike	1936	Dike: 83.5 ft long 10 ft wide Culvert: None	675.3 ft	813.2
	Three Bridges Dike	Structure listed as “abandoned” in 1986 USACE report	Unknown	Unknown	LVR channel below Vermillion Slough
Truedale Slough	Truedale Slough Dike	1936 Rebuilt in 1986-87	Dike: 150 ft long Culvert: 282.5 ft long 48in diameter No slope	Dike 676.5 ft Culvert Unknown	808.5
Carter Slough	Carter Slough Dike	1936 Rebuilt in 2002	Dike: 87 ft long Culvert: None	Initial 675.3 ft 1967 677.5 ft Current 679.0 ft	807.3
	DNR Dike	Unknown	Unknown	Unknown	
	Spot Dike K	1936	Dike: 101.75 ft long 64 ft wide	675.0ft	

Data obtained from drawings and other information obtained from the U.S. Army Corp of Engineers (USACE), St. Paul District, and the Minnesota Department of Natural Resources (MNDNR) Wildlife Management Division.

2.2 Historical Conditions

Modifications of the hydrologic regime of the Vermillion River Bottoms have had significant impacts on the suspended solids load and the associated turbidity of the LVR. The most notable change is associated with the impoundment of Mississippi Pool 3, beginning in 1936, which raised the stage of the Mississippi and created a tendency for water to flow from the Mississippi into the LVR. Other important changes include the urbanization of the Vermillion River and Mississippi River watersheds, climate trends, and changing agricultural practices. Historical data were assessed to determine the extent of the hydrologic changes and their potential effects on the suspended solids load and turbidity.

2.2.1 Aerial Photo Analysis

The LVR appears to have undergone significant changes in channel morphology and sediment transport due to anthropogenic influences and hydromodifications. Many of these changes have occurred since

[1] Considerable confusion can result from the use of different base elevation references. The USACE manages water levels in the navigational channel of the Mississippi in reference to the National Geodetic Vertical Datum (NGVD) of 1912, despite the fact that this datum has been superseded. As a result, NGVD 1912 is the default reference frame for work in this area, and elevations in other references are converted to NGVD 1912. Other commonly used reference frames include NGVD 1929, which is 0.5 foot lower than NGVD 1912 and is the basis for current topographic maps of the area. More recent work by USGS uses the North American Vertical Datum of 1988 (NAVD 1988), which adjusted to achieve a match between U.S., Canadian, and Mexican reference frames and does not have a constant conversion.

1938, the date of the earliest aerial photos. However, alterations to the floodplain and hydrology can also be observed in those historic photos. For example, in the aerial photo taken on July 18, 1938 (Figure 2-4), several cleared areas (possibly row crops or pasture land) can be observed on Prairie Island.

Figure 2-4 also suggests that the LVR appeared to carry a very high sediment load. This sediment would have been deposited on the floodplain during flood stage events, and the accumulation of excessive sediment in the channel caused the development of channel bars and islands, some of which were substantially vegetated. The gradient change in the slope of the landscape and stream is very low, and the river has a high sinuosity pattern and appears to be prone to migration during channel-forming bankfull flood events under natural conditions.

The confluence of the LVR and the Mississippi River is characteristic of a large delta fan. In the 1983 photos the LVR appears to be separated from the Mississippi River mainstem by a low-elevation natural levee, created by the deposition of excess sediments as the Mississippi River and LVR expand over their banks into the floodplain, drop stream velocity, decrease in energy, and deposit sediment. These natural deposits and levee formations extend along the floodplain of the Mississippi River, causing the LVR and Mississippi River to run parallel for some distance before they finally merge.

Figure 2-4. Portion of the LVR (near Clear Lake) from July 18, 1938 aerial photo.

As flood stages increase, the water levels rise over these natural levees, channel bars, and the land mass separating the LVR and Mississippi River. Several depressions in these near-stream land masses become inundated with large amounts of floodwaters and then gradually subside in stage as evaporation and groundwater percolation occurs. Some minimal permanent flow is present in the larger floodplain; there the elevation of the pond bottom is low enough to intersect the groundwater table, which is maintained at a high elevation by the impoundment of Pool 3.

Use of the nearby floodplains as agricultural lands in the 1920's and 1930's potentially could have lead to increased sediment inputs into the river. Figure 2-5 shows the confluence of several tributaries with the LVR in 1938. The photo shows the large sediment loads being deposited at these confluences as alluvial deposits and closer scrutiny shows large sediment deposits in the channel of the LVR just below the surface, along with several large bar developments.

Figure 2-5. LVR in 1938 aerial photo showing the Etter Bridge Area.

Figure 2-6 through Figure 2-8 are aerial views of the same section of the LVR near Carter Slough and Mud Hen Lake in 1938, 1992, and 2000, respectively. One apparent change during this time span appears to be a shift from agricultural land uses to residential development along the bluffs. The vegetative characteristics of the ponds appear to change, and the stage levels of the ponds seem to have become more permanent. Man-made structures have also developed to further control the hydrology of the river systems during regular and flood stages.

Figure 2-6. 1938 aerial photo image showing the Truedale Slough area.

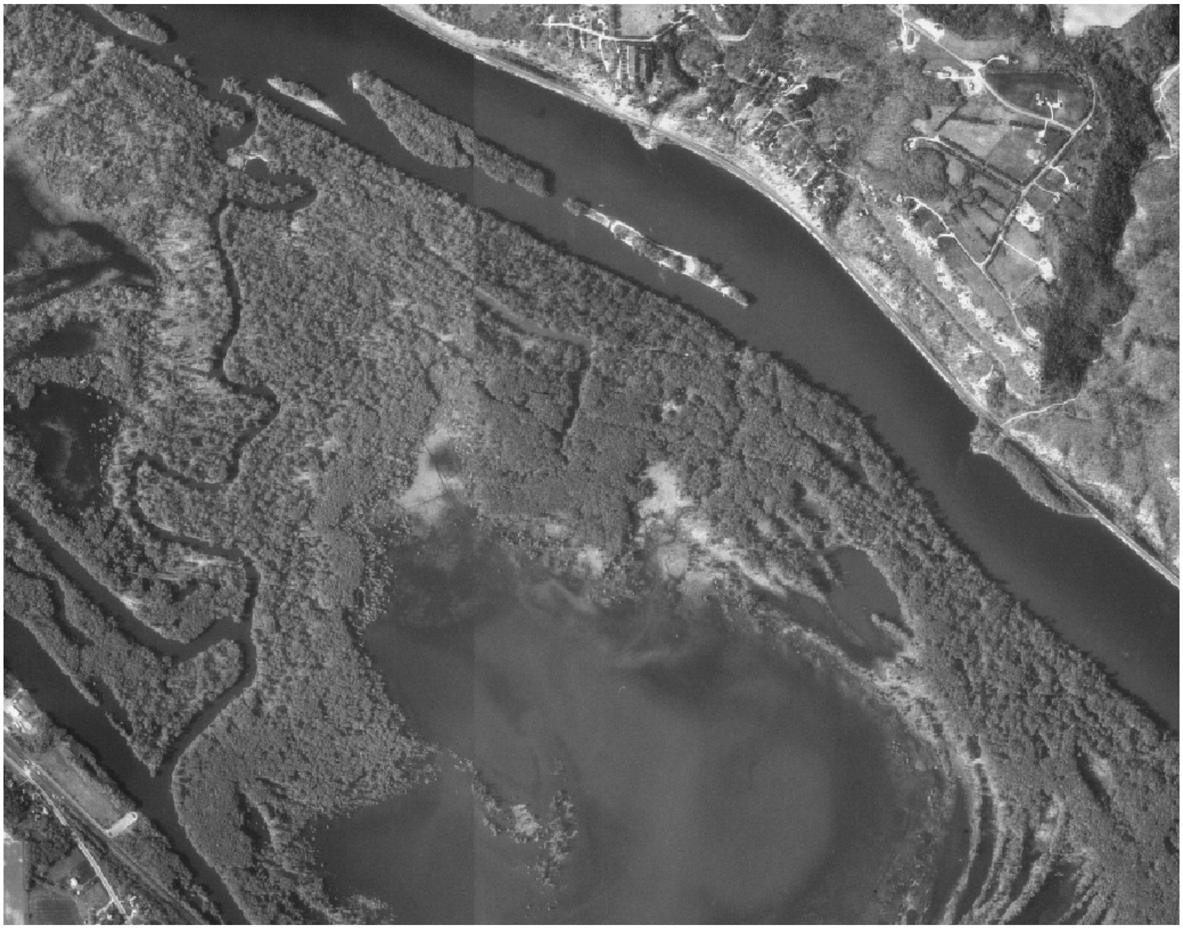


Figure 2-7. 1992 digital ortho quarter quad (DOQQ) image showing the Truedale Slough area.

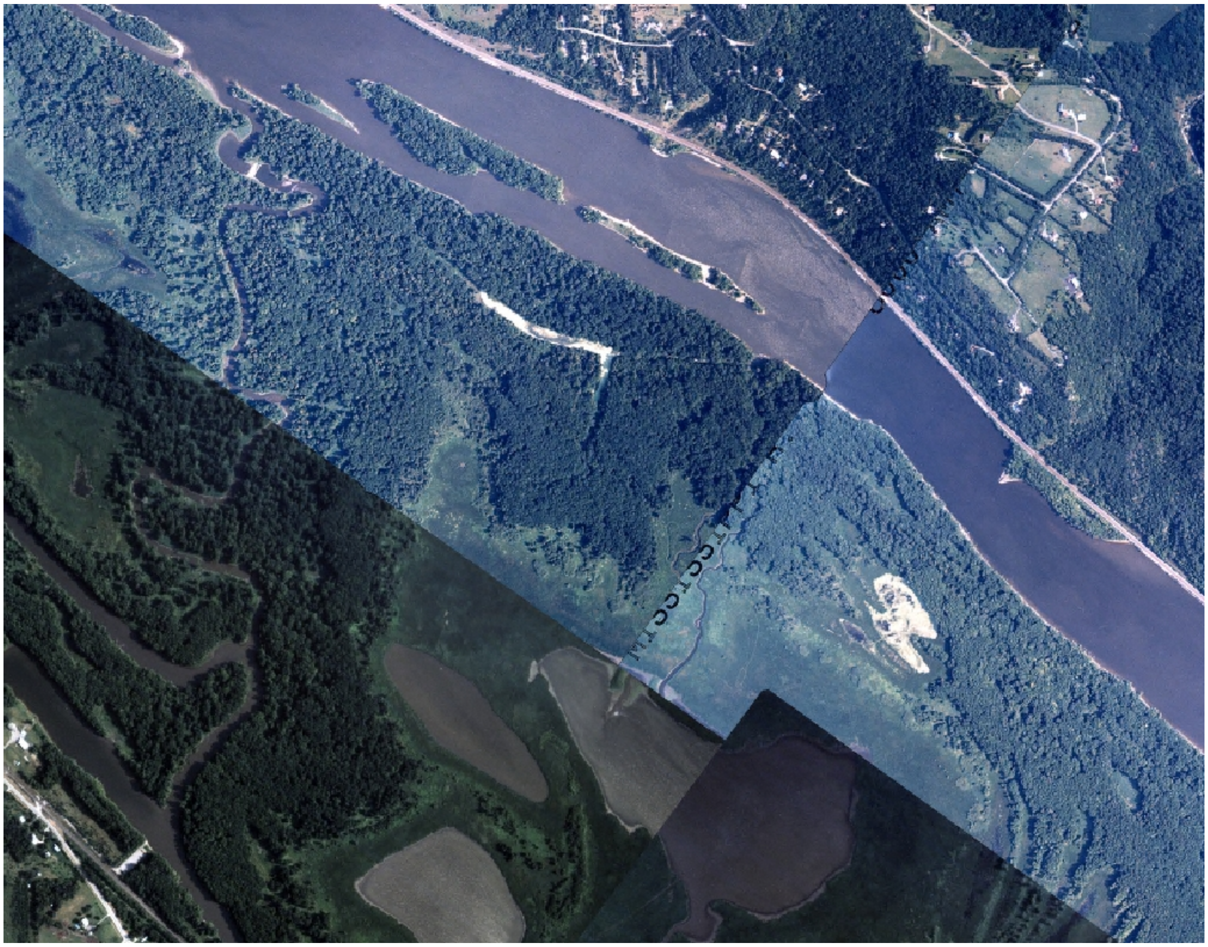


Figure 2-8. 2000 color mosaic image showing the Truedale Slough area.

In conclusion, a review of historic aerial photos reveals that the LVR was modified and influenced by human impacts prior to 1937-38. Since 1938 the LVR has undergone even more significant anthropogenic influences and changes to the hydrology, channel morphology, and floodplain corridor. The hydrology is very dynamic and complex, with subsurface flows and surface channels interconnected to the various ponds and rivers. The LVR appears to carry a large sediment load, which it deposits into bars and onto the floodplain during greater-than-bankfull flood events.

2.2.2 Hydrologic Alteration Due to Construction of Lock and Dams

To assess the hydrologic impacts due to lock and dam construction on the Mississippi River, a software package called the Indicators of Hydrologic Alteration (IHA) (Nature Conservancy, 2001) was used. The IHA requires a data series corresponding to a water year (October through September) of daily stream gauge records for pre- and post-impact periods in the stream system of interest. The IHA computes statistics for a period of record that may be used to examine flow regime characteristics. Five main groups of hydrologic attributes are computed for each year of the pre-impact and the post-impact data series by the IHA, as presented in Table 2-2. Additionally, the IHA computes measures of central tendency and measures of dispersion for 32 parameters in each data series, thereby producing 64 inter-annual statistics useful in the comparison of pre- and post-impact hydrologic conditions.

Table 2-2. Summary of hydrologic parameters computed in the Indicators of Hydrologic Alteration.

IHA Statistics Group	Regime Characteristics	Hydrologic Parameters
Group 1: Magnitude of monthly flow conditions	Magnitude Timing	Median value for each month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means
Group 3: Timing of annual extreme flow conditions	Timing	Julian date of each annual 1-day minimum Julian date of each annual 1-day maximum
Group 4: Frequency and duration of high and low pulses	Magnitude Frequency Duration	Number of high pulses each year Number of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year
Group 5: Rate and frequency of water flow conditions	Frequency Rate of change	Means of all positive differences between consecutive daily means Means of all negative differences between consecutive daily means Number of rises Number of falls

The U.S. Geological Survey (USGS) has collected daily stream flow measurements for the Mississippi River at Prescott, Wisconsin (05344500) since 1928, and historical stream flow data are available from 1928 to 2002. The streamflow gage at Prescott reflects a drainage area of approximately 44,800 square miles. Hydrologic impacts to the Mississippi River first occurred in 1930 when Lock and Dam 2 was constructed and were further experienced when Lock and Dam 3 was finalized in 1938. Therefore, for purposes of this analysis, the pre-impact period is defined as prior to 1930 and the post-impact period is defined as after 1938.

To compare pre-impact and post-impact periods, the IHA method suggests that 20 years of daily flow records should be available for both time periods. However, only two years of pre-impact flow data (1928 to 1930) are available for the Prescott gage. To increase the pre-impact flow record at Prescott, data from the USGS gage at St. Paul (05331000) were used to statistically extrapolate flow. The stream gage at St. Paul is located approximately 20 miles upstream from Prescott, and daily mean stream flow data are available for the period 1892 to 2002. Corresponding daily mean flow data are therefore available for Prescott and St. Paul for the period 1928 to 1930.

The corresponding flows were used to define a statistical relationship between the two data sets. The relationship was developed through bivariate linear regression analysis. The relationship at St. Paul and Prescott, as well as the regression results, are shown in Figure 2-9. The figure shows that a strong relationship exists between flows recorded at the two gages ($R^2 = 0.89$). However, the relationship weakens when stream flows at Prescott exceed 25,000 cfs. Consequently, the regression was re-run with Prescott stream flows greater than 25,000 cfs, and the paired observations from St. Paul, excluded from the analysis. A total of 50 coupled observations, representing five percent of the total data set, were excluded from the analysis. Historically, 78 percent of the mean daily stream flows recorded at Prescott from 1928 to 2002 are less than 25,000 cfs. Regression results from this slightly reduced data set are presented in Figure 2-10.

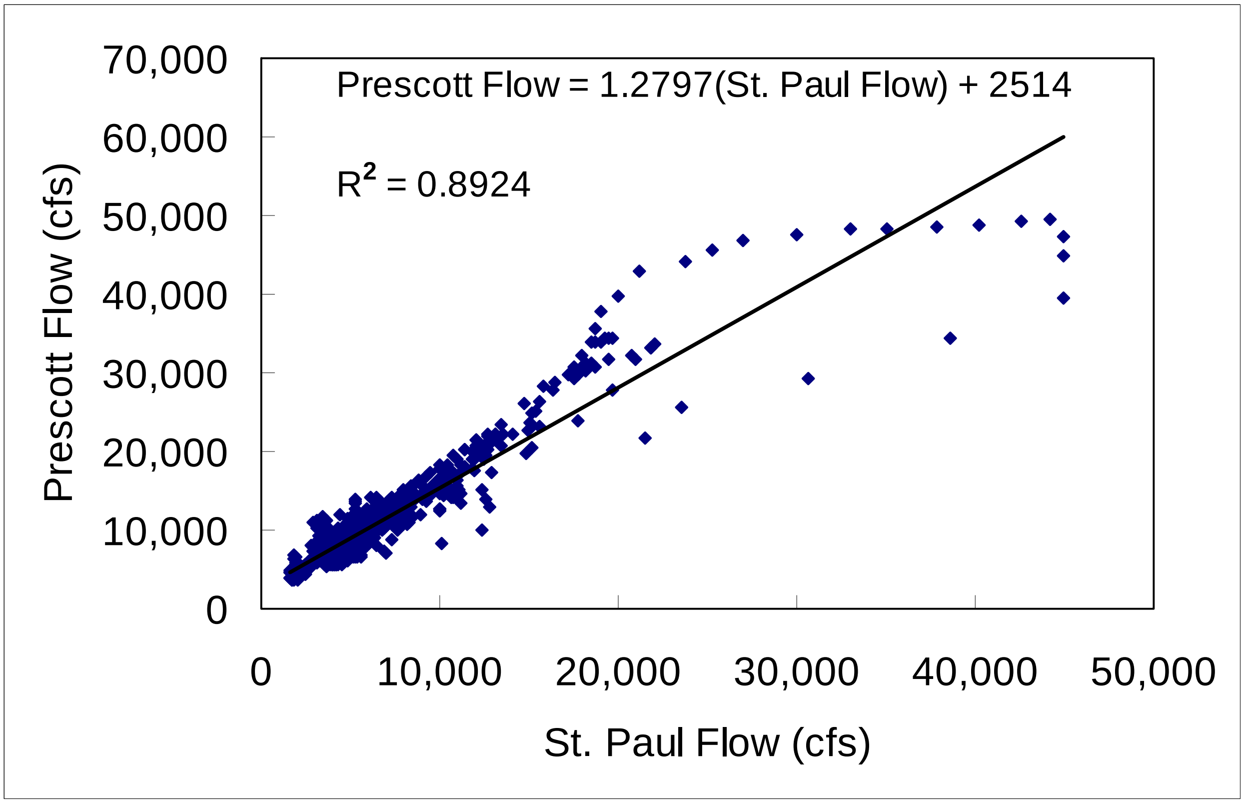


Figure 2-9. Regression results for St. Paul and Prescott stream gages. All data included.

A strong relationship between the stream records at St. Paul and Prescott is illustrated in Figure 2-10. Although the level of agreement between the two data sets has slightly weakened, with R-square decreasing to 0.86, the relationship is still strong. Indeed, 86 percent of the variability between stream flow measured at St. Paul and at Prescott is expressed by the regression equation.

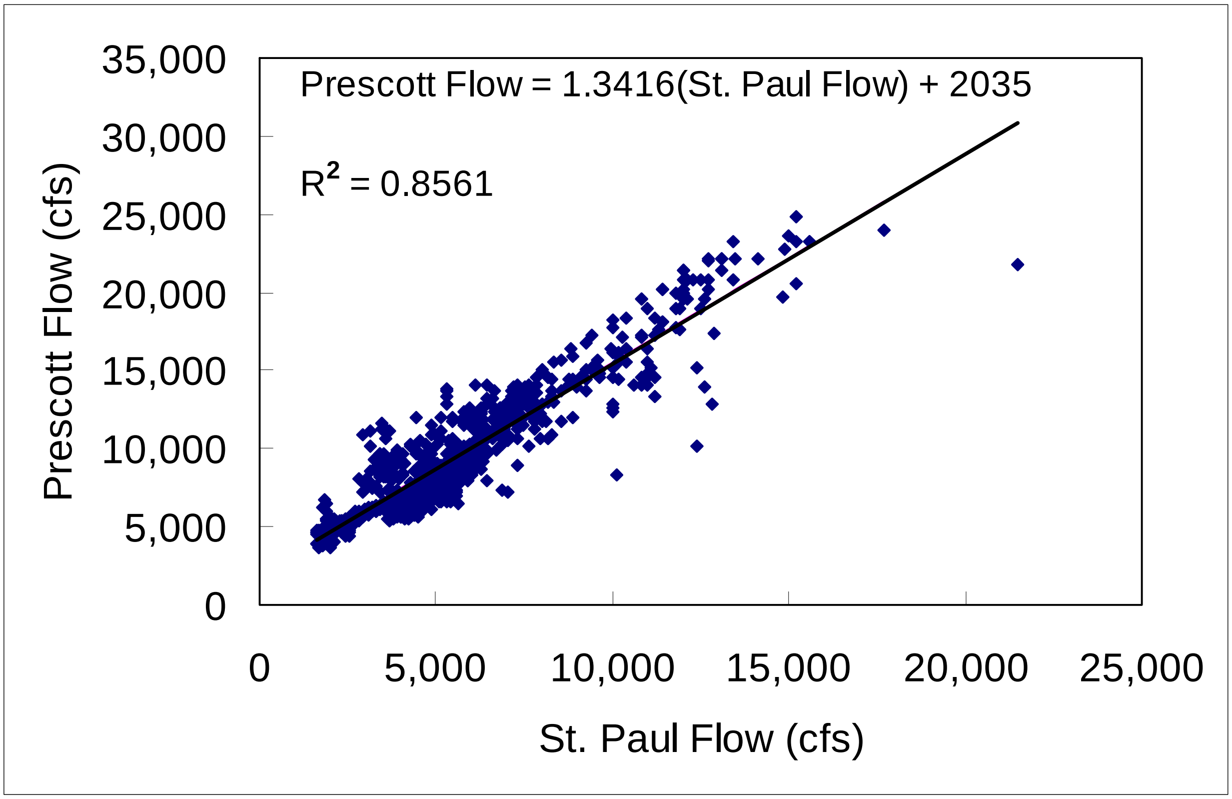
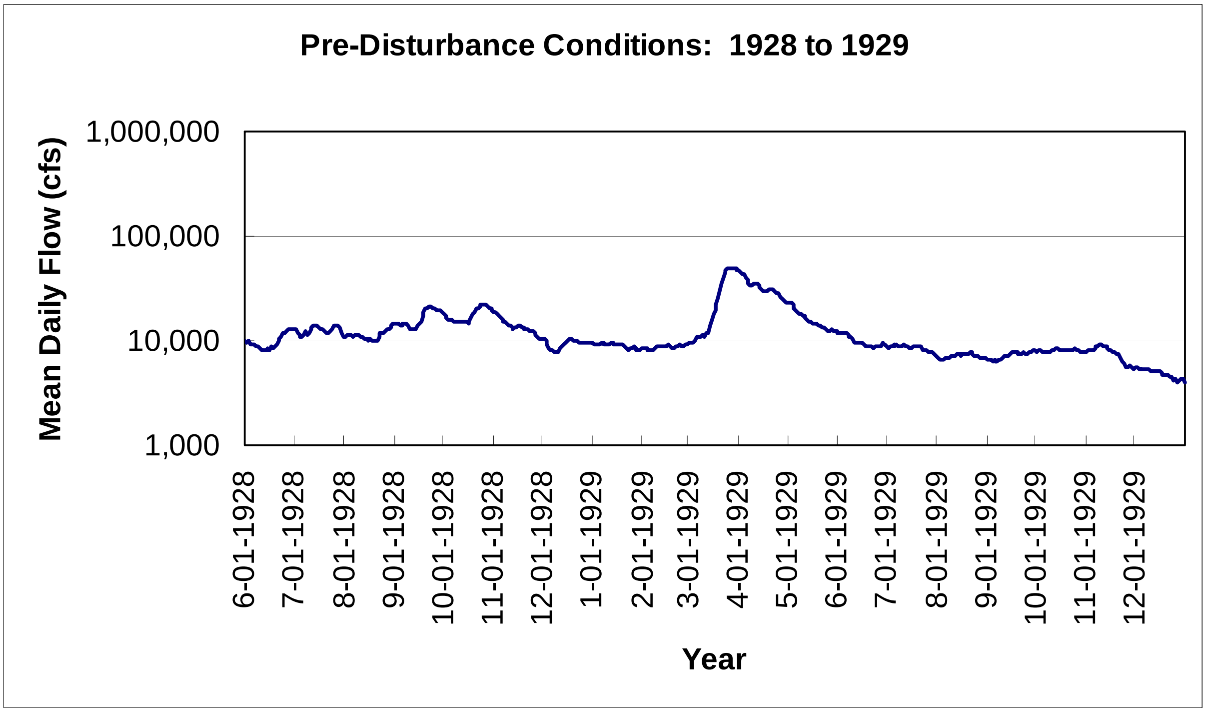


Figure 2-10. Regression results for St. Paul and Prescott stream gages. Flows > 25,000 cfs excluded.

The regression equation given in Figure 2-10 was used to predict stream flow at the Prescott station from 1901 to 1928, thereby extending the pre-impact stream flow record. The record of daily mean stream flows at St. Paul from 1892 to 1900 have several periods of missing data. Consequently data from this time period were not used to extend the pre-impact stream flow record at Prescott.

The pre-impact period has therefore been defined as 1901 to 1930, and the post-impact period is 1938 to 2002. For comparative purposes, pre- and post-dam hydrographs for an 18-month period are presented in Figure 2-11. The figure suggests that flow conditions have significantly changed at the Prescott gage for the two time periods. Specifically, mean flows appear to have increased dramatically at Prescott in post-dam conditions. This assumption is further evaluated with the use of the IHA.



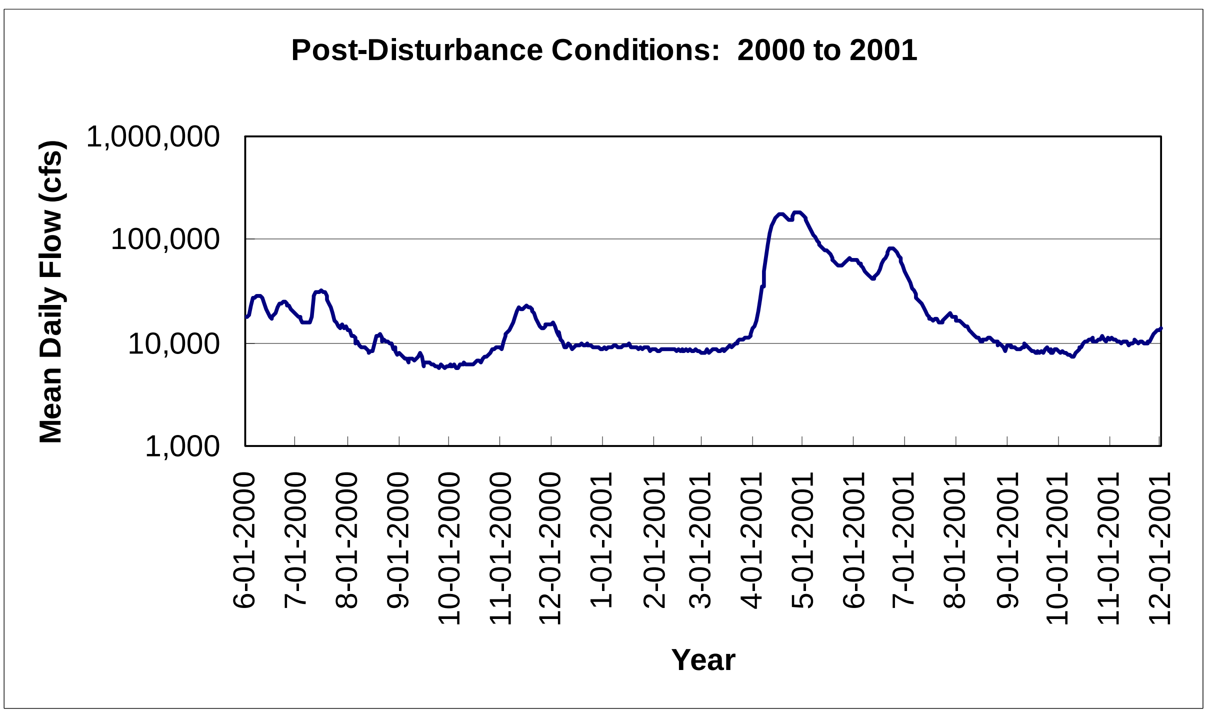


Figure 2-11. Mean daily stream flow at Prescott, Wisconsin, for pre- and post-impact conditions.

The IHA results for the Mississippi River at Prescott, Wisconsin are given in Table 2-3 and illustrated in Figure 2-12 through Figure 2-15. Table 2-3 and Figure 2-12 show that changes in monthly median stream flow have occurred from pre-impact conditions to post-impact conditions. Monthly median stream flow increased in all months except October (Parameter Group 1) with the greatest increases occurring in April and July. Median stream flows increased by 104 percent, 64 percent, and 55 percent for the months of April, July, and May, respectively (Parameter Group 1, column 5). Additionally, Figure 2-13 and Figure 2-14 show that variability in median monthly stream flow decreased during the winter season, while variability increased during spring, summer and fall seasons from pre-impact to post-impact conditions.

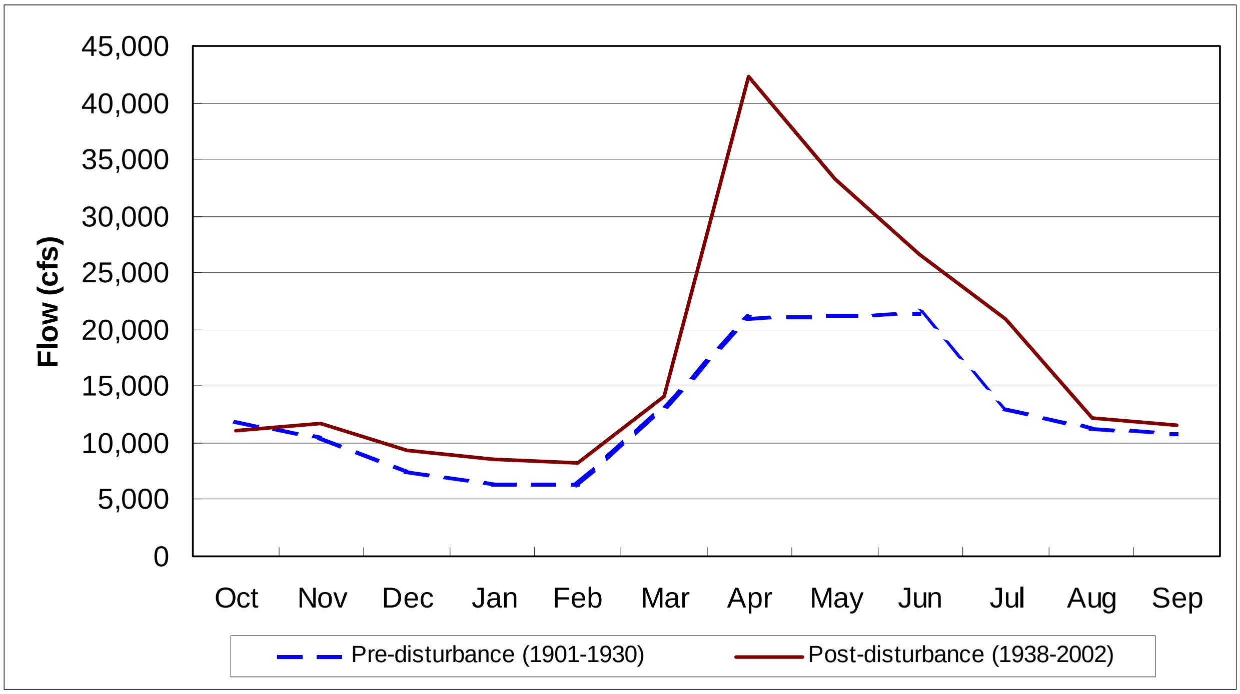


Figure 2-12. Median monthly stream flow for pre- and post-impact conditions.

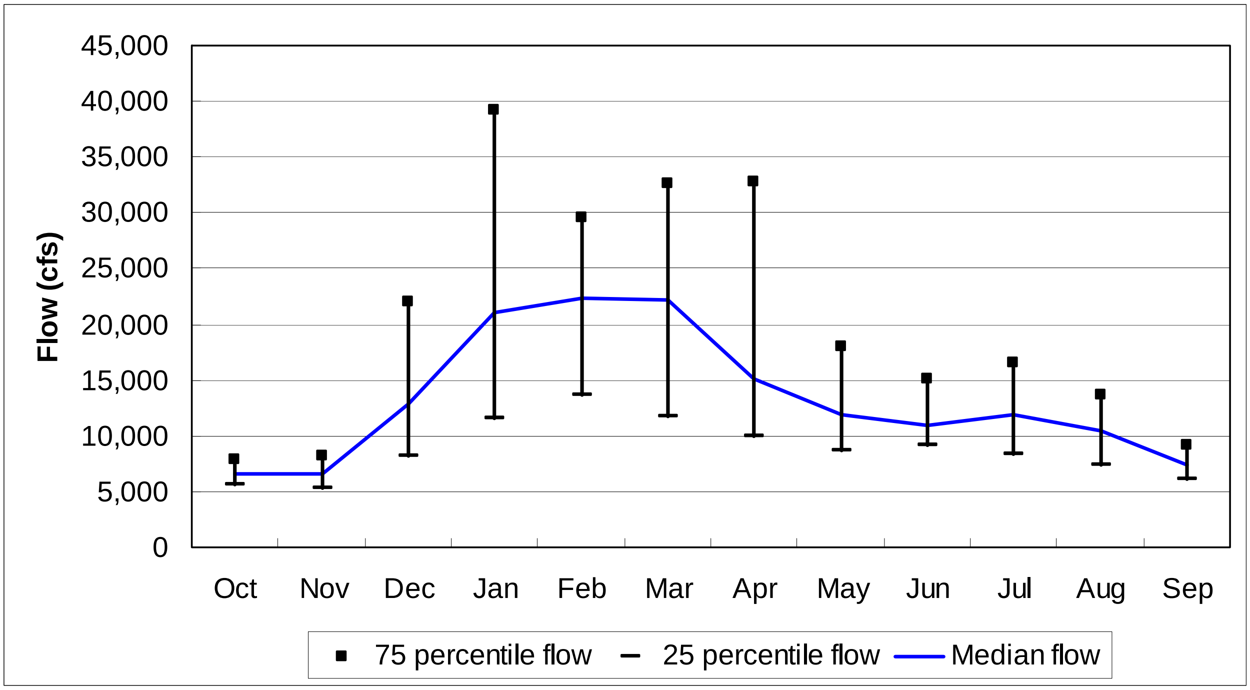


Figure 2-13. Variability in monthly median stream flow during pre-impact conditions.

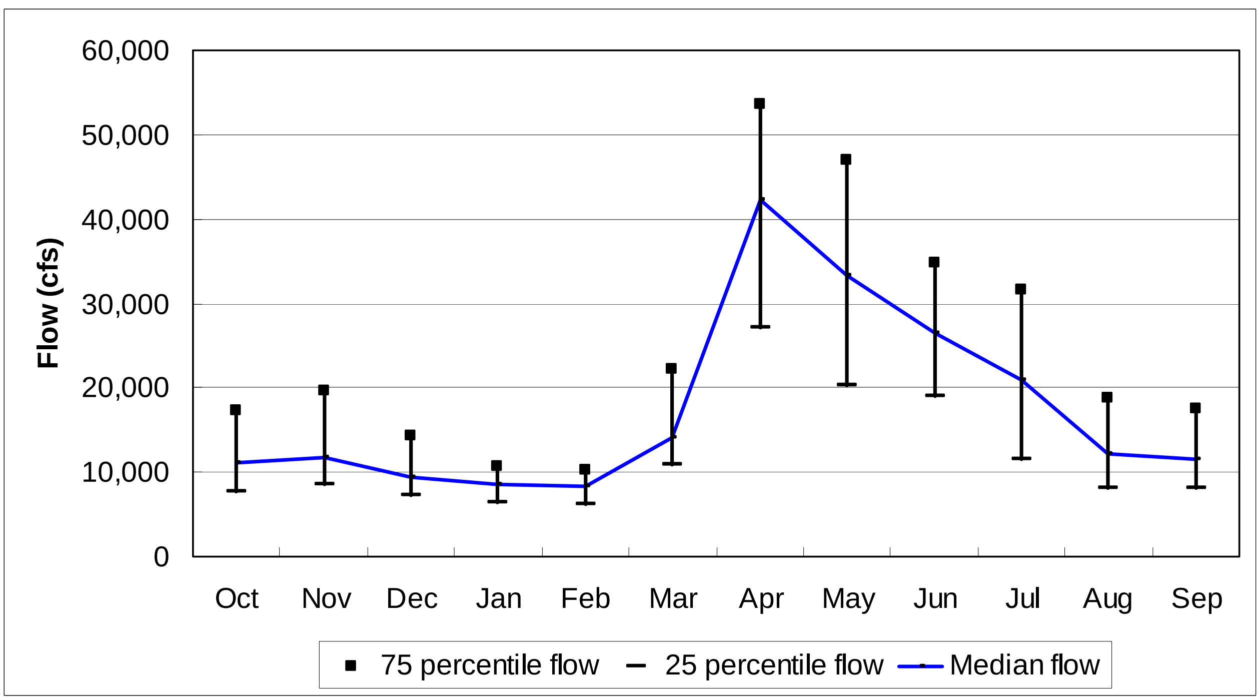


Figure 2-14. Variability in monthly median stream flow during post-impact conditions.

The magnitude and duration of annual flow extremes also changed significantly from pre-impact to post-impact conditions (Table 2-3, Parameter group 2). Overall, minimum flows have very slightly increased, while maximum flows have significantly increased (Figure 2-15). The timing of multi-day minimum and maximum flows has also changed (Parameter Group 3). Minimum flows occur 11 months later (on November 26 (Julian day 330)) compared to pre-impact conditions. Maximum flow occurs slightly earlier (on April 21 (Julian day 111)) in post-impact conditions, while in pre-impact conditions maximum flow occurred on May 9 (Julian day 129).

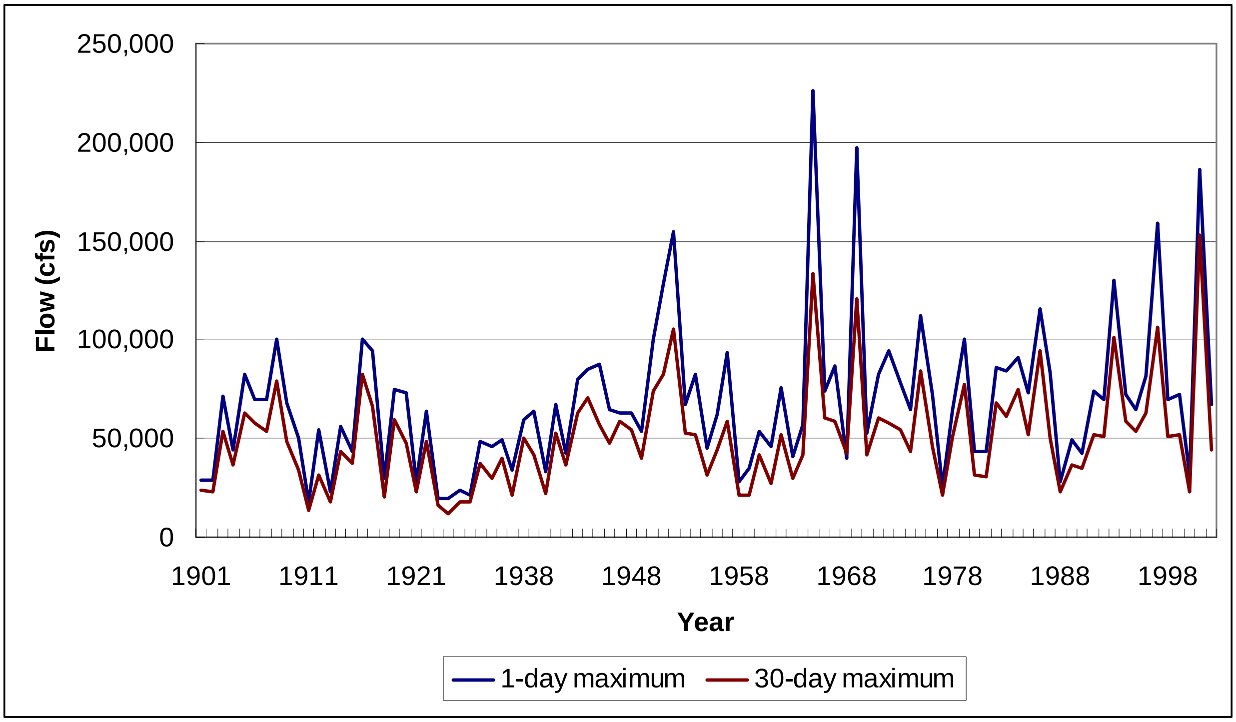


Figure 2-15. Multi-day maximum stream flows from 1901 to 2002 at Prescott, Wisconsin.

Table 2-3 also suggests strong changes in the rate and frequency of stream flow conditions from pre- to post-impact conditions (Parameter Group 5). The average hydrograph rise rate and fall rate increases in post-impact conditions and fall rates (Parameter Group 5). This suggests that changes in flow recorded at the Prescott gage have become much greater in post-impact conditions resulting in a much more variable system.

Table 2-3. Results of the Indicators of Hydrologic Alteration for the Mississippi River at Prescott, Wisconsin.

Parameter	Median Flow (cfs)		Coefficient of Dispersion[a]		Deviation Factor[b]	
	Pre	*Post*	Pre	Post	*Medians*	*C.V.*
Group #1						
October	11816	11106	0.72	0.86	0.06	0.20
November	10473	11905	0.6	0.93	0.14	0.54
December	7418	9590	0.45	0.72	0.29	0.60
January	6322	8549	0.34	0.51	0.35	0.52
February	6292	8339	0.44	0.49	0.33	0.12
March	13250	14150	1.01	0.81	0.07	0.20
April	20936	42653	1.38	0.59	1.04	0.57
May	21292	32977	0.72	0.82	0.55	0.14
June	21333	26472	0.98	0.6	0.24	0.38
July	13062	21355	1.89	0.95	0.63	0.50
August	11322	12634	0.86	0.86	0.12	0.00
September	10728	11368	0.68	0.84	0.06	0.24
Group #2						
1-day minimum	5678	5485	0.35	0.55	0.03	0.60
3-day minimum	5678	5748	0.34	0.56	0.01	0.62
7-day minimum	5678	5877	0.32	0.49	0.04	0.57
30-day minimum	5898	6802	0.27	0.48	0.15	0.76
90-day minimum	6413	7840	0.23	0.48	0.22	1.08
1-day maximum	49832	71050	0.87	0.47	0.43	0.45
3-day maximum	49425	70317	0.87	0.47	0.42	0.46
7-day maximum	48491	68329	0.87	0.45	0.41	0.48
30-day maximum	37695	51863	0.9	0.4	0.38	0.55
90-day maximum	26577	39323	0.85	0.56	0.48	0.34
Number of zero days	0	0	0	0		
Base flow	0.4	0.3	0.42	0.28	0.27	0.32
Group #3						
Date of minimum	25	330	0.13	0.25	0.33	0.89
Date of maximum	129	111	0.21	0.15	0.07	0.27
Group #4						
Low pulse count	2.5	5	2.5	1.4	1.00	0.44
Low pulse duration	20.2	3.4	2.71	3.35	0.83	0.24
High pulse count	2	4	1.13	0.75	1.00	0.33
High pulse duration	26.3	31.1	1.00	0.95	0.18	0.05
The low pulse threshold is	7,139					
The high pulse level is	18,167					
Group #5						
Rise rate	827	1,171	1.03	0.45	0.42	0.56
Fall rate	-705	-947	-0.84	-0.33	0.34	0.61
Number of reversals	75	124	0.94	0.27	0.64	0.72

[a]Coefficient of Dispersion = (75^{th} percentile– 25^{th} percentile) / 50^{th} percentile
[b]Deviation Factor = [(Post-impact value) – (Pre-impact value)] / (Pre-impact value)

3 WATER QUALITY CONCERNS AND STATUS

This section of the document presents the 303(d) list status of the LVR, followed by a description of the applicable water quality standards and a waterbody-by-waterbody review of available data.

3.1 Minnesota 303(d) List Status

The Lower Vermillion River appears on Minnesota's EPA-approved 2002 303(d) list for turbidity and PCBs (due to a fish consumption advisory). The affected use is aquatic life, and the target completion date for TMDL development is 2005.

3.2 Applicable Water Quality Standards

Minnesota adopted its first statewide water quality standards in 1967. These standards have been updated by adding new standards and regulations periodically since then. The comprehensive Clean Water Act amendments of 1972 require states to adopt water quality standards that meet the minimum requirements of the federal Clean Water Act. Minnesota's water quality standards meet or exceed the federal requirements.

Under the Clean Water Act, every state must adopt water quality standards to protect, maintain, and improve the quality of the nation's surface waters. These standards represent a level of water quality that will support the act's goal of "fishable and swimmable" waters. Water quality standards consist of three components: beneficial uses, numeric or narrative standards, and a nondegradation policy. Minnesota's water quality standards are summarized in Table 3-1 and explained in greater detail below.

Table 3-1. Minnesota Water Quality Standards

Component	Description
Beneficial use	Beneficial uses are the uses that states decide to make of their water resources. The process of determining beneficial uses is spelled out in the federal rules implementing the Clean Water Act.
Numeric standards	Numeric water quality standards represent safe concentrations in water that protect a specific beneficial use. If the standard is not exceeded, the use should be protected.
Narrative standards	A narrative water quality standard is a statement that prohibits unacceptable conditions in or on the water, such as floating solids, scums, visible oil film, or nuisance algae blooms. Narrative standards are sometimes called "free froms" because they help keep surface waters free from fundamental, basic types of water pollution.
Nondegradation	(equivalent to the federal term "antidegradation"). The fundamental concept of nondegradation is that lakes, rivers, and streams whose water quality is better than the applicable standards should be maintained at that high level of quality and not allowed to degrade to the level of applicable standards.

Water quality standards and related provisions can be found in several Minnesota rules, but the primary rule for statewide water quality standards is Minnesota Rules Chapter 7050. Included in this rule are the following:

- A classification system of beneficial uses for both surface and groundwaters
- Numeric and narrative water quality standards
- Nondegradation provisions

- Provisions for the protection of wetlands
- Treatment requirements and effluent limits for wastewater discharges
- Other provisions related to protecting Minnesota's water resources from pollution

Although portions of the Vermillion River upstream of Hastings (township ranges 19 and 20) are designated Class 2A (trout streams), the LVR (ranges 16 and 17) is not specifically listed in the rules and therefore has a default classification of 2B. The Minnesota Rules specify that Class 2B surface waters must permit the propagation and maintenance of a healthy community of cool or warm water sport or commercial fish and associated aquatic life and their habitats. The chronic turbidity standard for Class 2B waters is 25 NTU. The chronic standard is defined as the highest concentration of a toxicant to which aquatic organisms can be exposed indefinitely with no harmful effects, or to which humans or wildlife consumers of aquatic organisms can be exposed indefinitely with no harmful effects. Minnesota Pollution Control Agency's (MPCA) assessment methodologies indicate that less than 10 percent of all observations must be below the standard to result in full support of the beneficial use. Historically, approximately 33 percent of all turbidity observations in the LVR have exceeded 25 NTU. The goal of implementing the TMDL is for less than 10 percent of all future turbidity observations to be less than 25 NTUs.

3.3 Parameters of Concern

The following sections provide a summary of the parameters related to the turbidity impairment in the LVR. The purpose of this information is to provide an overview of the parameters, units, sampling methods, and potential sources for these parameters for readers who might not be familiar with them. The relevance of each parameter to the various beneficial uses is also briefly discussed.

3.3.1 Turbidity

Turbidity is defined as a measure of water clarity that refers to the scattering of light by suspended matter, dissolved organic compounds, and plankton in the water. If water becomes too turbid, it loses the ability to support a wide variety of plants and other aquatic organisms. Suspended particles can also clog fish gills, which lowers their resistance to disease, lowers their growth rates, and affects egg and larval development. The turbidity measurement is used as an indirect indicator of the concentration of suspended matter, and it can also be important for evaluating the available light for photosynthetic use by aquatic plants and algae.

Turbidity is measured by passing a light beam into a water sample and measuring the photons received at a 90 degree offset. This reflection of light is a direct result of the suspended materials in the water sample that the light encounters as it passes through the sample. The results are reported as nephelometric turbidity units or NTU.

One challenge associated with using turbidity as a TMDL target is that both organic and inorganic particles affect water clarity. Organic particles can result from a healthy biological community and thus can distort the interpretation of high turbidity readings. Furthermore, organic particulates also vary seasonally, with higher concentrations occurring during the summer months. These variations introduce variability into turbidity measurements and their relationship to other variables. That is, turbidity readings are affected more by the organic particulates present in the water at certain times of the year, such as the summer. Another complicating factor associated with interpreting turbidity data is that values might vary throughout the water column. For example, turbidity might be high at the surface due to organic matter and phytoplankton, low in the middle of the water column, and high again at the bottom due to inorganic minerals.

3.3.2 Total Suspended Solids

TSS is used to quantify concentrations of suspended solid-phase material in surface waters. TSS data are produced by several laboratory methods, most of which entail measuring the dry weight of sediment from a known volume of a subsample of the original. The measurements are reported in milligrams per liter (mg/L). Suspended-sediment concentration (SSC) is also used to quantify concentrations of suspended solid-phase material, but the analytical method differs from that used for TSS. SSC data are produced by measuring the dry weight of all the sediment from a known volume of a water-sediment mixture. A study by the USGS (2000) found that TSS typically under-estimates solid-phase materials at higher values and recommended SSC as a more reliable measurement.

As TSS settles to the bottom of a stream, critical habitats such as spawning sites and macroinvertebrate habitats can be covered by sediment. Excess sediment on a stream bottom can reduce dissolved oxygen concentrations in stream bottom substrates and can reduce the quality and quantity of habitats for aquatic organisms.

Erosion and overland flow contribute some natural TSS to most streams. In watersheds with highly erodible soils and steep slopes, natural TSS concentrations can be very high. Excess TSS in overland flow can also occur when poor land use and land cover practices are in place. Sources of TSS include grazing, row crops, agriculture, construction activities, road runoff, and mining. TSS loadings can also occur as a result of streambed erosion.

3.3.3 Total Phosphorus

Total phosphorus is a nutrient necessary to sustain aquatic life. The natural amount of total phosphorus in a waterbody varies depending on the type of system. A pristine headwaters spring might have little to almost no total phosphorus, whereas a lowland, mature stream flowing through wetland areas might have naturally high total phosphorus concentrations. Various forms of phosphorus can be present at one time in a waterbody, although not all forms can be used by aquatic life. Common phosphorus sampling parameters are total phosphorus (TP), dissolved phosphorus, and orthophosphate. Concentrations are measured in the lab and are typically reported in milligrams per liter.

Total phosphorus usually does not pose a direct threat to the beneficial uses of a waterbody. Excess phosphorus can, however, cause an undesirable abundance of plant and algae growth. This process is called eutrophication or nutrient enrichment. Nutrient enrichment (eutrophication) can have many detrimental effects on water quality. One possible effect of eutrophication is low dissolved oxygen concentrations. Aquatic organisms need oxygen to live, and they can experience lowered reproduction rates and mortality with lowered dissolved oxygen concentrations. Recreational uses can also be impaired because of eutrophication. Nuisance plant and algae growth can interfere with swimming, boating, and fishing.

Phosphorus is present in rocks and soils and is naturally weathered and transported into waterbodies. Organic matter is another natural source of nutrients. Systems rich with organic matter (e.g., wetlands and bogs) can have naturally high nutrient concentrations. Phosphorus can also be released into the environment through different anthropogenic sources, such as septic systems, wastewater treatment plants, fertilizer application, and animal feeding operations.

3.3.4 Chlorophyll *a*

Chlorophyll *a*, the dominant pigment in algal cells, is a valuable surrogate indicator for algal biomass (Carlson, 1980). Chlorophyll *a* is desirable as a water quality indicator because algae are either the direct (e.g., nuisance algal blooms) or indirect (e.g., high or low dissolved oxygen and pH, and high turbidity) cause of most problems related to excessive nutrient enrichment.

3.4 Review of Available Water Quality Data

A major focus of Phase I activities was to compile and assess all existing water quality data related to the LVR. Monitoring data were requested and obtained from a number of agencies, including MPCA, MNDNR, the USGS, the Metropolitan Council Environmental Services (MCES), the USACE, the Wisconsin Department of Natural Resources, the Prairie Island Indian Community, and the Xcel Energy power plant. All these data were reformatted into a consistent format and compiled into one master database to facilitate analysis. The sections below provide a review of the available data organized according to the waterbodies of interest:

- Vermillion River
- Sloughs
- Off-Channel and On-Channel Lakes
- Mississippi River

The locations of all the sampling stations discussed in this section are shown in Figure 3-1 and the stations located only in the LVR are shown in Figure 3-2.

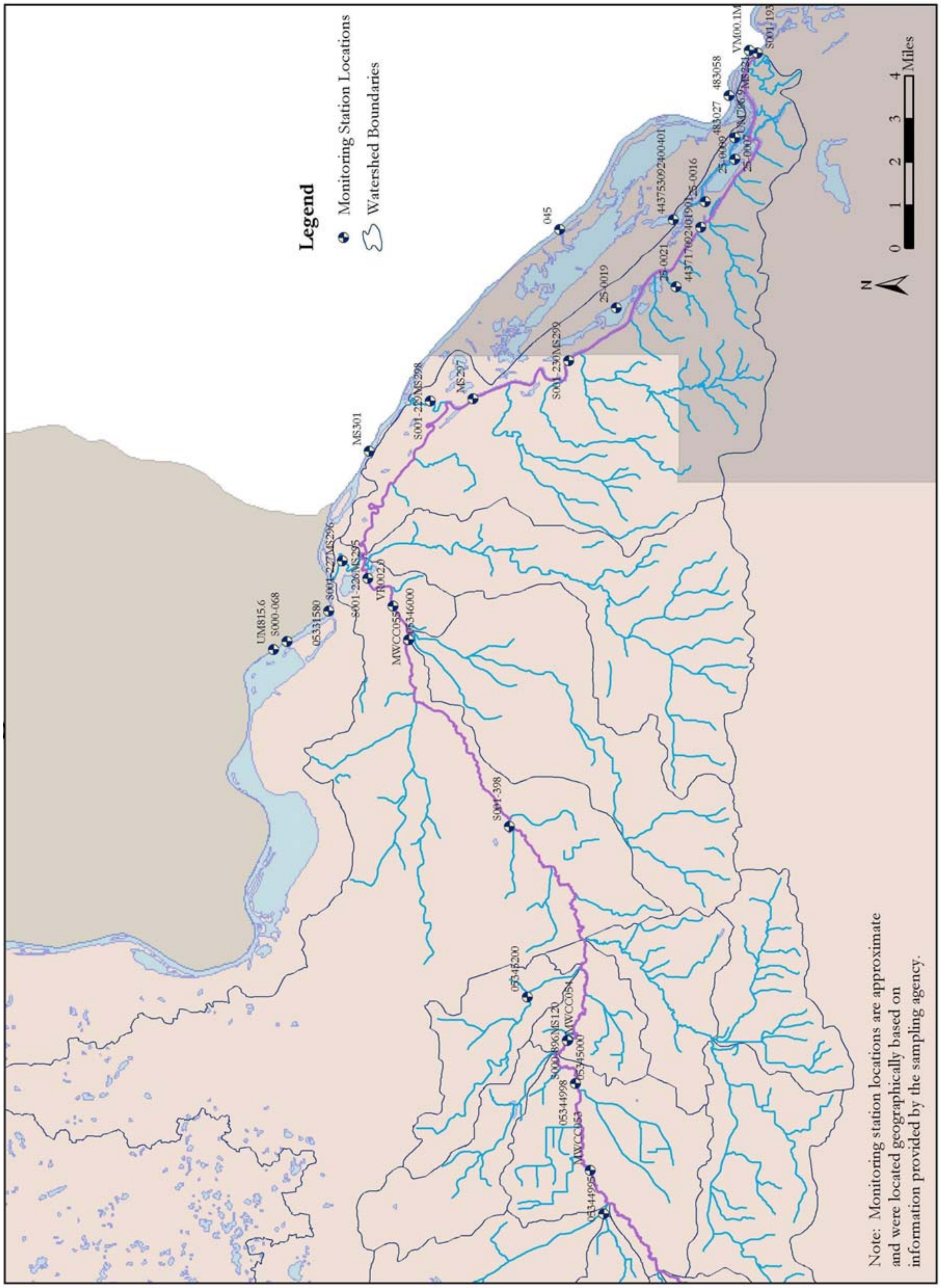


Figure 3-1. Location of all sampling stations.

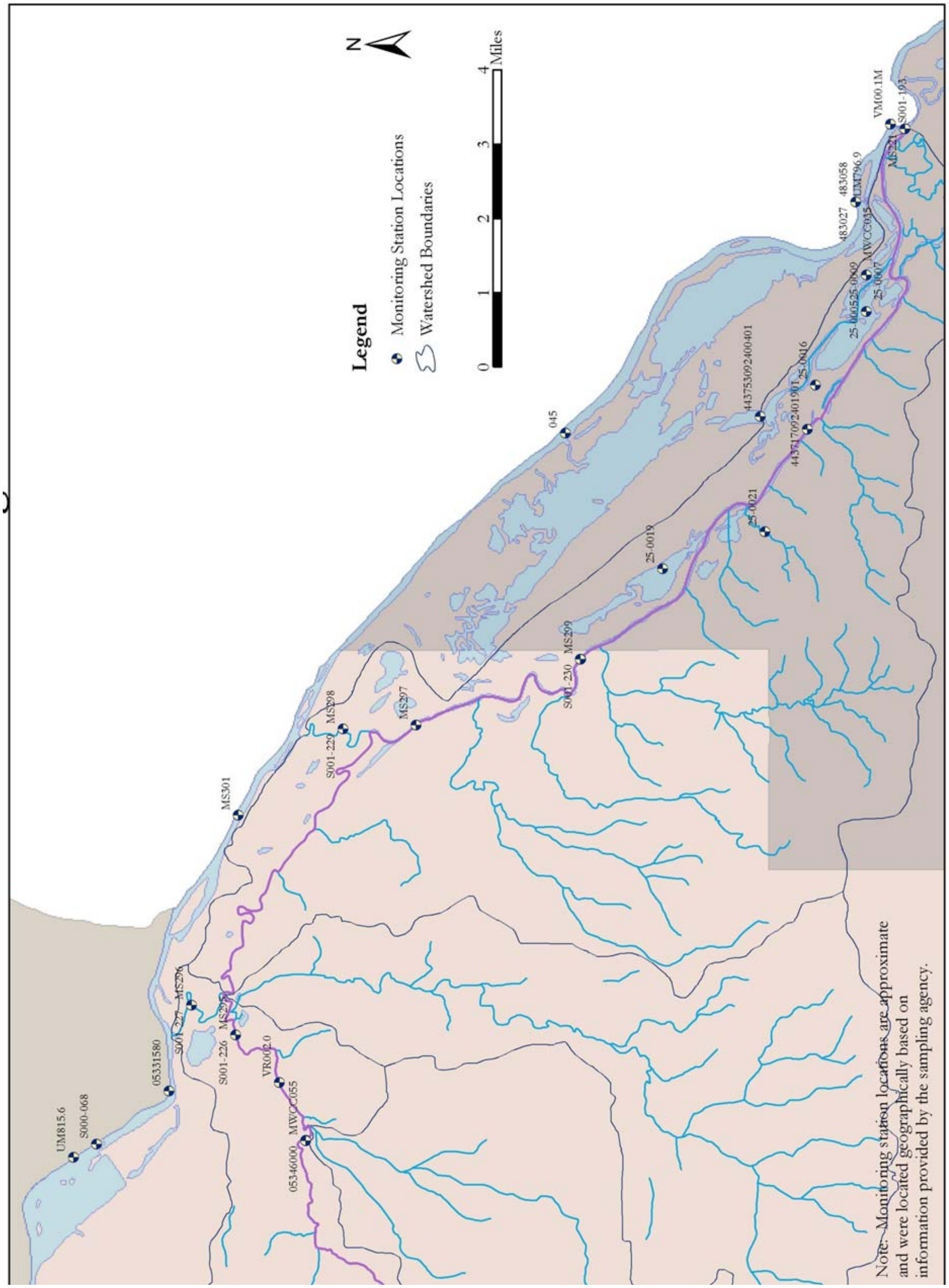


Figure 3-2. Location of LVR sampling stations.

3.4.1 Vermillion River

Water quality data have been collected at 21 different stations on the Vermillion River, Including 11 upstream of Hastings and 10 downstream. The period of record and total number of all observations for all parameters are shown in Table 3-2. The table indicates that the stations with the most data are those near Farmington, Empire, and Hastings and at the confluence with the Mississippi River. Of these stations, recent data are available for the stations at Hastings and at the confluence with the Mississippi River.

Table 3-2. Period of Record for Water Quality Stations on the Vermillion River

Agency	Station ID	Station Name	First Date Sampled	Last Date Sampled	Number of Observations (All Parameters)
Met Council	MWCC053	Vermillion River at Biscayne Ave. bridge, 1 mile northeast of	1/9/1985	12/16/1992	4270
Met Council	MWCC054	Vermillion River at CR-79 near Empire	1/9/1985	12/16/1992	4121
Met Council	MWCC055	Vermillion River at CR-47 near Hastings	1/9/1985	12/20/2001	3021
Met Council	VR2.0	Vermillion River 150m down from HWY61	4/20/1995	11/10/2003	2447
MPCA	MS120	Vermillion River bridge on Blaine Ave. 4 miles northeast of Farmington	10/27/1981	11/9/1998	2787
MPCA	MS221	Vermillion River 01. mile upstream of Cannon River confluence near Red	4/30/1990	9/28/1992	1270
MPCA	MS295	Vermillion River at highway 54, 7/8 mile southeast of Hastings	6/12/1995	9/9/1998	111
MPCA	MS297	Vermillion River southeast ¼ S5, 5 mile southeast of Hastings	6/12/1995	9/9/1998	118
MPCA	MS299	Vermillion River at highway 68 bridge, ¾ mile northeast of Etter	6/12/1995	9/9/1998	129
MPCA	S000-896	Vermillion River bridge on Baline Ave. 4 miles northeast Farmington	1/19/1999	9/4/2001	206
MPCA	S001-193	Vermillion River 0.1 upstream of Cannon River confluence near Red	7/25/2001	7/25/2001	14
MPCA	S001-226	Vermillion River at Highway 54, 7/8 mile southeast of Hastings	5/29/2001	7/25/2001	27
MPCA	S001-230	Vermillion River at highway 68 bridge, ¾ mile northeast of Etter	7/25/2001	7/25/2001	14
MPCA	S001-398	Vermillion River at CSAH-85 bridge 1 mile northeast of Vermillion	3/28/1999	9/30/2001	289
USACE	VR002.0	Vermillion River at River Mile 2River Mile	6/6/1994	12/30/1996	123
USGS	05344995	Vermillion River tributary near Farmington	3/14/1990	5/16/1991	219
USGS	05344998	Vermillion River below Empire	9/17/2001	9/17/2001	81
USGS	05345000	Vermillion River below Empire	10/6/1972	3/21/1997	3169
USGS	05345200	Vermillion River below Empire	3/15/1990	5/16/1991	63
USGS	05346000	Vermillion River near Hastings	3/25/1967	5/17/1991	3147
USGS	443717092 401901	Vermillion River (SW6) at Prairie Island	8/1/1995	4/30/1996	56
USGS	VM00.1M	Vermillion River at mouth	1/24/1990	9/18/2002	5861

Table 3-3 summarizes the available turbidity data for the station at Hastings and all stations on the LVR. The most observations are available at the USGS station at the mouth of the LVR and at the USACE station 2 miles upstream. Average turbidity at these two stations is approximately 22 NTU and 8 NTU, respectively. Average turbidity values for all observations in the Upper Vermillion River are approximately 9 NTU.

Table 3-3. Summary of Available Turbidity (NTU) Data for the Vermillion River

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (NTU)	Average (NTU)	Maximum (NTU)
MS221	4/30/1990	9/28/1992	51	3	21.64	50
MWCC055	4/1/1998	12/20/2001	60	0.8	9.59	90
S000-896	1/19/1999	9/4/2001	20	2.1	7.9	20
S001-193	7/25/2001	7/25/2001	1	33	33	33
S001-226	5/29/2001	7/25/2001	2	7.8	8.5	9.2
S001-230	7/25/2001	7/25/2001	1	27	27	27
VM00.1M	1/24/1990	9/18/2002	414	2	21.99	89
VR2.0	3/31/1998	11/10/2003	103	0.8	8.14	90

All the turbidity data for the mouth of the LVR (station VM00.1M) are plotted in Figure 3-3. There does not appear to be a noticeable increasing or decreasing trend over the period of record, and approximately 40 percent of the samples at this station exceed 25 NTU.

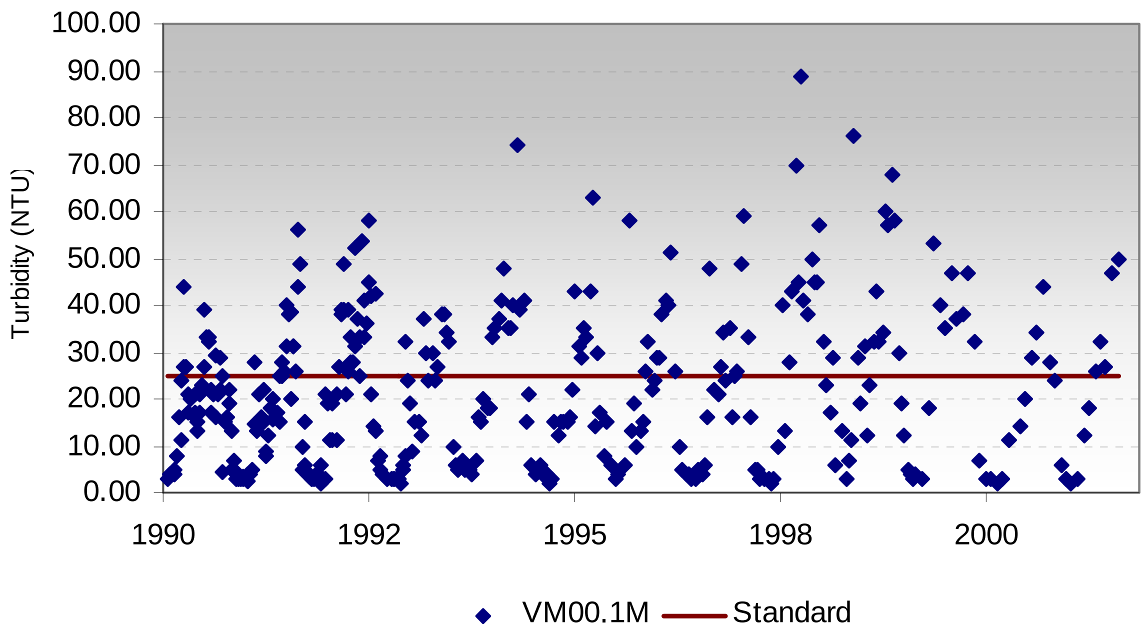


Figure 3-3. All turbidity observations for the Vermillion River at the mouth (VM00.1M) over the period January 24, 1990, to September 18, 2002.

The average monthly turbidity data for station VM001.M are shown in Figure 3-4. Average, median, minimum, and maximum values for each month are plotted on this graph. It is apparent that turbidity steadily increases from March through the summer and then peaks in September. Average and median values in June, July, August, September, and October all exceed the standard. Few data are available for the winter months.

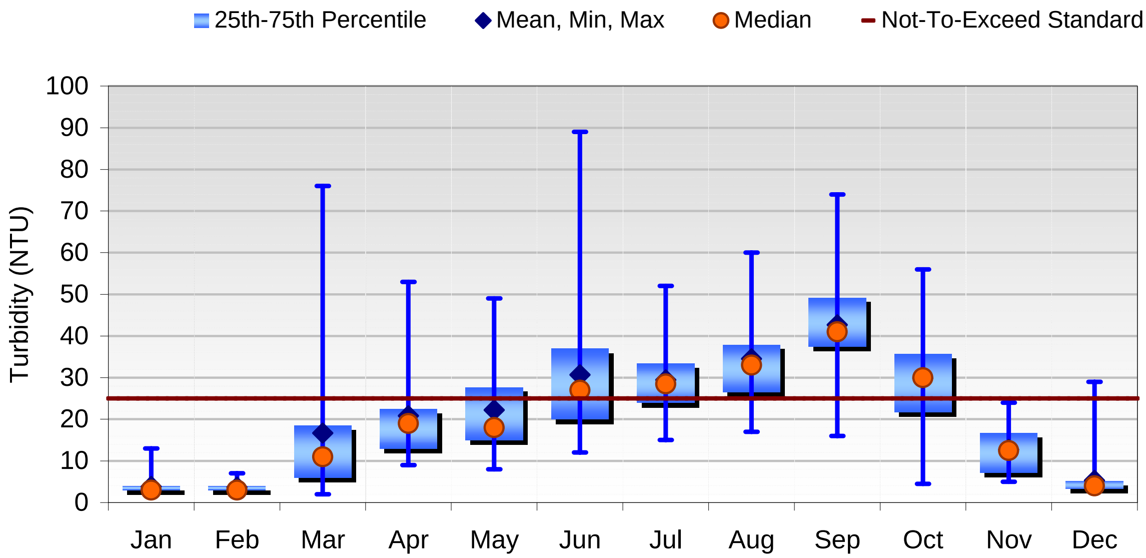


Figure 3-4. Monthly turbidity observations for the Vermillion River at the mouth (VM00.1M) over the period January 24, 1990, to September 18, 2002.

Table 3-4 summarizes the available TSS data for the entire Vermillion River. Several stations have more than 100 observations, and average concentrations range from approximately 9 mg/ at Empire to 50 mg/L at Hastings. The average TSS for all stations in the Upper Vermillion River is approximately 12 mg/L. Average TSS at Hastings, however, is much higher, at approximately 50 mg/L. The average TSS for stations in the LVR is 35 mg/L.

Table 3-4. Summary of Available TSS Data for the Vermillion River

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)
5345000	10/16/1972	12/15/1976	49	0	16.67	64
5346000	10/16/1972	12/15/1976	49	0	22.92	128
MS120	10/27/1981	8/22/1996	125	0.6	15.13	340
MS221	4/30/1990	9/28/1992	36	3.2	32.84	59
MS295	7/13/1995	8/23/1995	2	35	38.5	42
MS297	7/13/1995	8/23/1995	2	43	54.5	66
MS299	7/13/1995	8/23/1995	2	62	67.5	73
MWCC053	1/23/1985	12/16/1992	191	1	8.96	146
MWCC054	1/9/1985	12/16/1992	185	1	9.36	65
MWCC055	4/20/1995	12/20/2001	114	2	50.18	214
S000-896	3/29/1999	9/4/2001	17	3.2	21.41	51
S001-193	7/25/2001	7/25/2001	1	47	47	47
S001-226	5/29/2001	7/25/2001	2	13	16	19
S001-230	7/25/2001	7/25/2001	1	49	49	49
VR002.0	6/6/1994	12/30/1996	63	2.6	28.68	184.5
VM00.1M	4/28/1993	9/18/2002	184	1.7	28.25	75.7
VR2.0	4/20/1995	11/10/2003	137	2	45.15	214

All the TSS data from station VM00.1M are plotted in Figure 3-5. There does not appear to be a noticeable increasing or decreasing trend over the period of record.

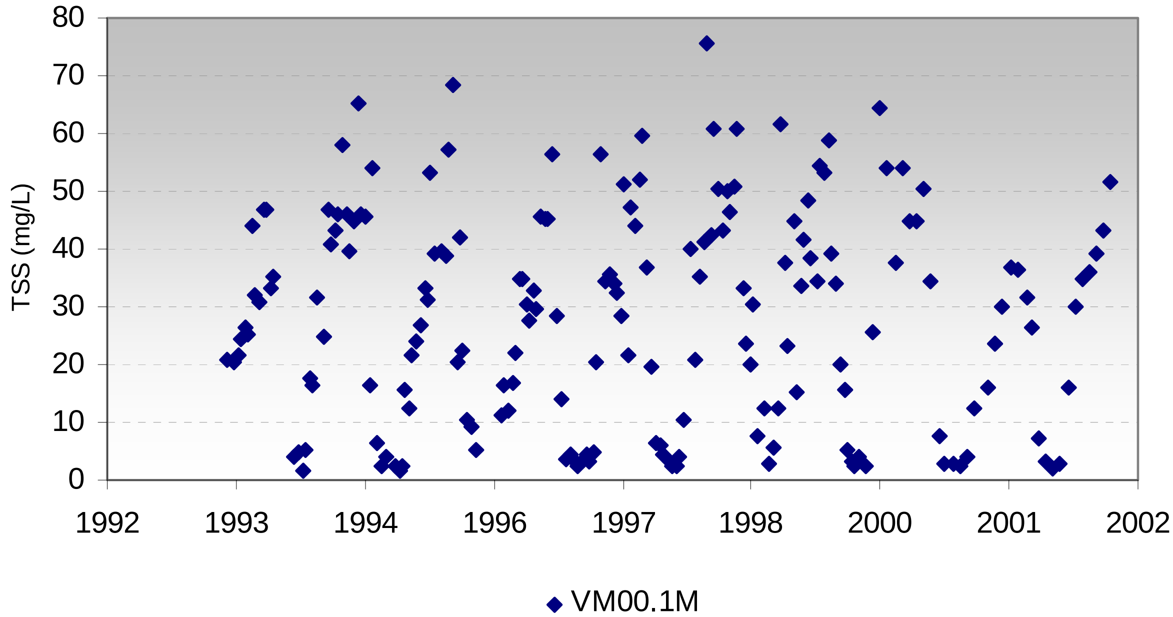


Figure 3-5. All TSS observations from the Vermillion River at the mouth (VM00.1M) over the period April 28, 1993, to September 18, 2002.

The average monthly TSS data from station VM001.M are shown in Figure 3-6. The TSS concentrations follow the e seasonal trend of the turbidity values: concentrations increase steadily from March through September and then decrease in October. Few data are available for the winter months.

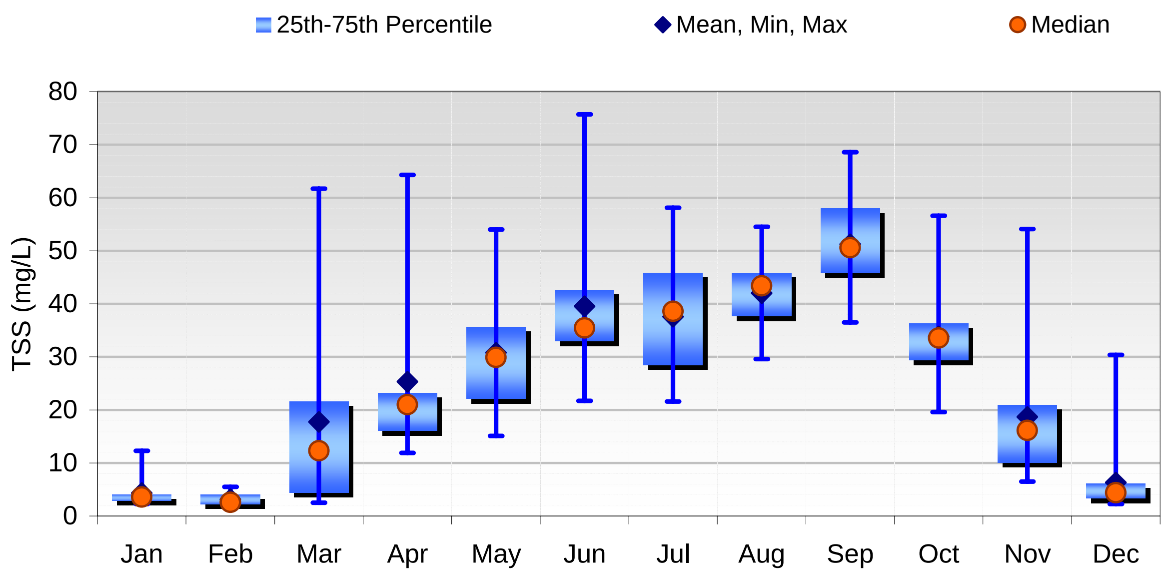


Figure 3-6. Monthly TSS observations for the Vermillion River at the mouth (VM00.1M) over the period April 28, 1993, to September 18, 2002.

All the TSS data for the Upper Vermillion River near Hastings (station MWC055) are plotted in Figure 3-7. The data for 2001 appear to be slightly less variable and lower than earlier data, although the overall period of record does not indicate an increasing or decreasing trend.

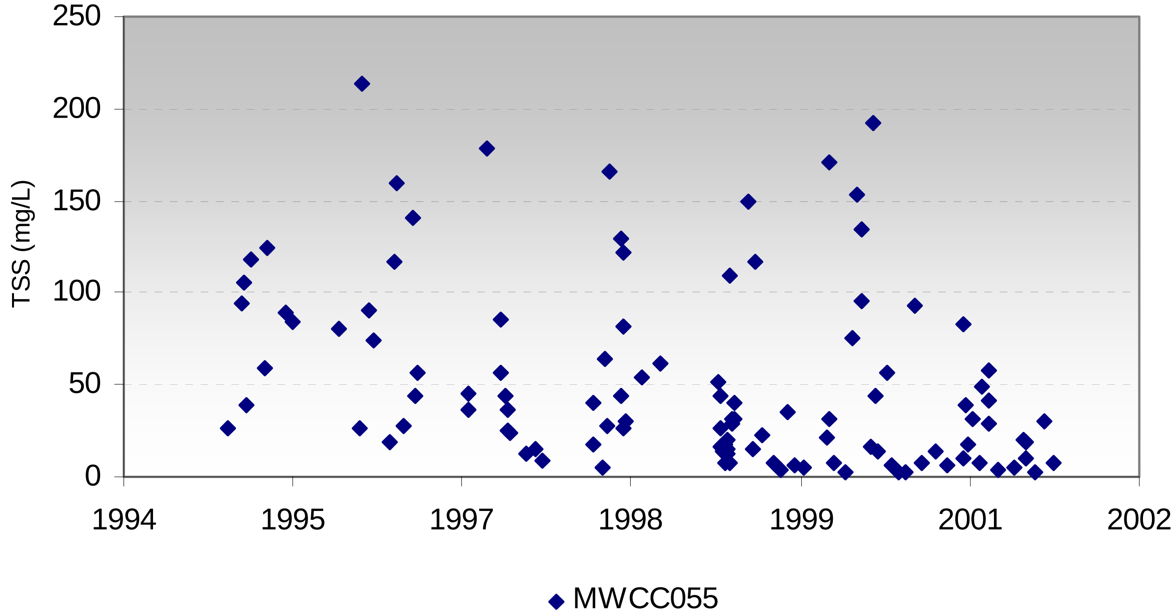


Figure 3-7. All TSS observations at the Vermillion River at CR-47 near Hastings (station MWC055) over the period April 20, 1995, to December 20, 2001.

The average monthly TSS data for station MWC055 are shown in Figure 3-8. The trend is not the same as the turbidity or TSS data for the mouth of the LVR. Instead, the values increase from April to June, but then decreasing from July to September.

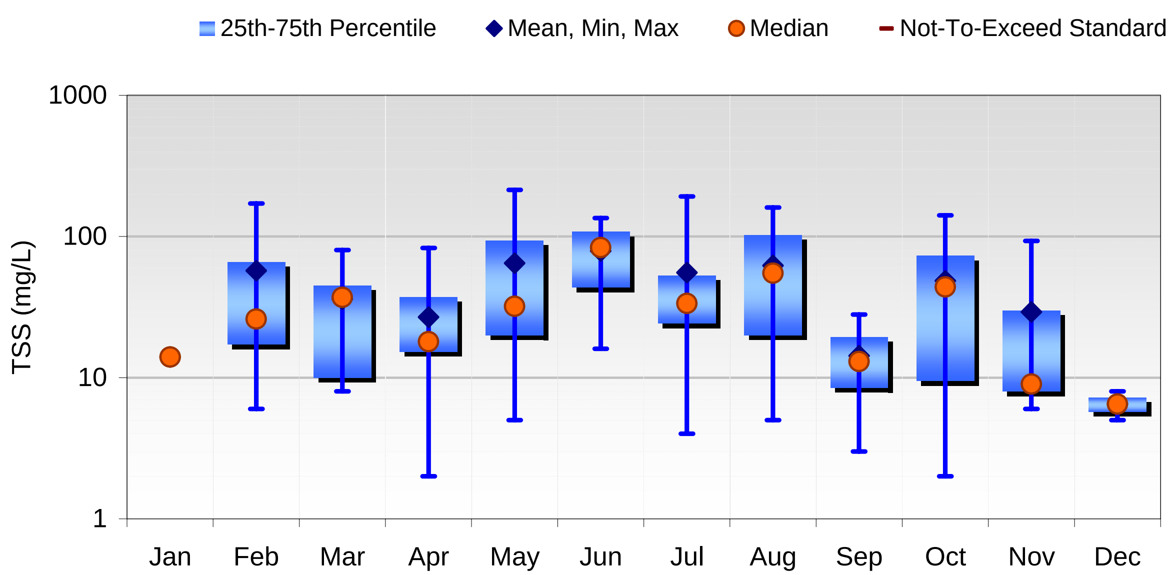


Figure 3-8. Seasonal TSS concentrations for the Vermillion River at CR-47 near Hastings (station MWC055) over the period April 20, 1995, to December 20, 2001.

Table 3-5 summarizes the available TP data for the entire Vermillion River. Average TP concentrations at the various sites range from 0.09 mg/L to 1.06 mg/L. The average TP for all Upper Vermillion River stations is 0.63 mg/L, and the average for all LVR stations is 0.34 mg/L.

Table 3-5. Summary of Available Total Phosphorus Data for the Vermillion River

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)
05344995	3/14/1990	5/16/1991	10	0.04	0.12	0.45
05345000	1/14/1974	3/21/1997	16	0.4	0.84	2.1
05345200	3/15/1990	5/16/1991	3	0.1	0.11	0.13
05346000	1/15/1974	5/17/1991	14	0.43	0.64	1.6
443717092401901	8/1/1995	4/30/1996	2	0.07	0.09	0.11
MS120	10/27/1981	11/9/1998	127	0.07	0.85	3.06
MS221	4/30/1990	9/28/1992	54	0.09	0.26	0.42
MS295	7/13/1995	9/9/1998	5	0.31	0.45	0.61
MS297	7/13/1995	9/9/1998	5	0.32	0.35	0.42
MS299	7/13/1995	9/9/1998	5	0.29	0.31	0.36
MWCC053	1/23/1985	12/16/1992	220	0.01	0.1	2.06
MWCC054	1/9/1985	12/16/1992	209	0.01	1.06	6.5
MWCC055	4/6/1990	12/20/2001	181	0.02	0.62	4
VM00.1M	6/11/1991	9/18/2002	224	0.025	0.22	1.253
VR2.0	4/20/1995	10/24/2003	135	0.02	0.56	4

All the TP data for station VM00.1M at the mouth of the LVR are plotted in Figure 3-9. Most TP levels are between approximately 0.10 mg/L and 0.40 mg/L. The four data points above 0.60 mg/L were recorded between March 13, 1996, and November 12, 1996. Why these four samples were so much greater than all the other samples is unknown.

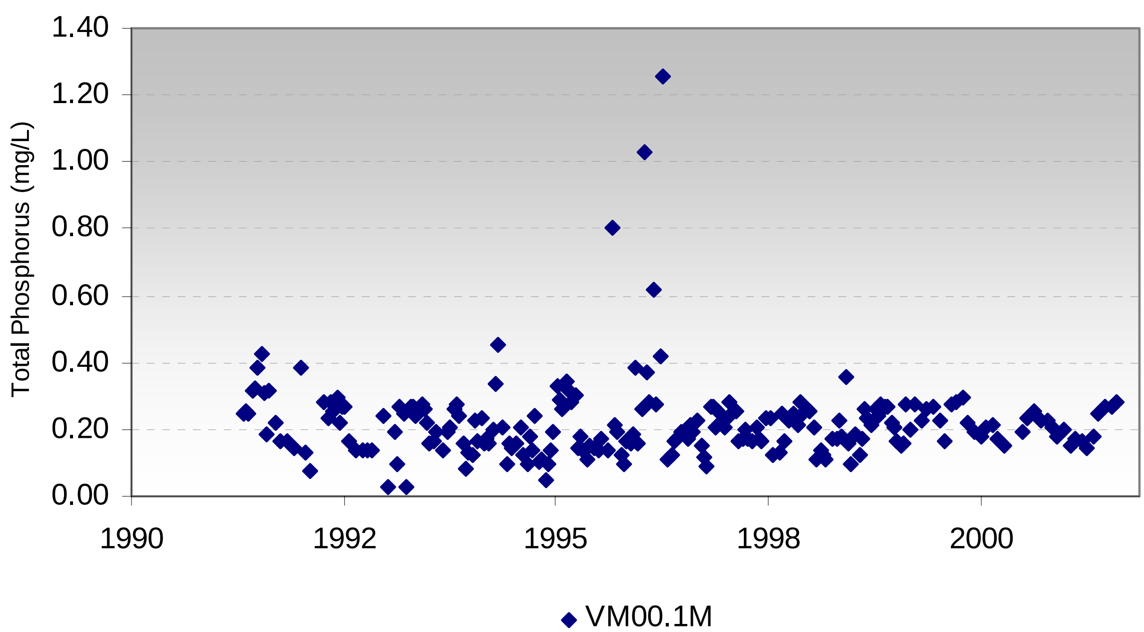


Figure 3-9. All TP observations for the Vermillion River at the mouth (VM00.1M) over the period June 11, 1991, to September 18, 2002.

The average monthly TP data for station VM00.1M are shown in Figure 3-10. Average values are highest in August (0.30 mg/L) and September (0.30 mg/L) and lowest in April (0.15 mg/L) and May (0.15 mg/L).

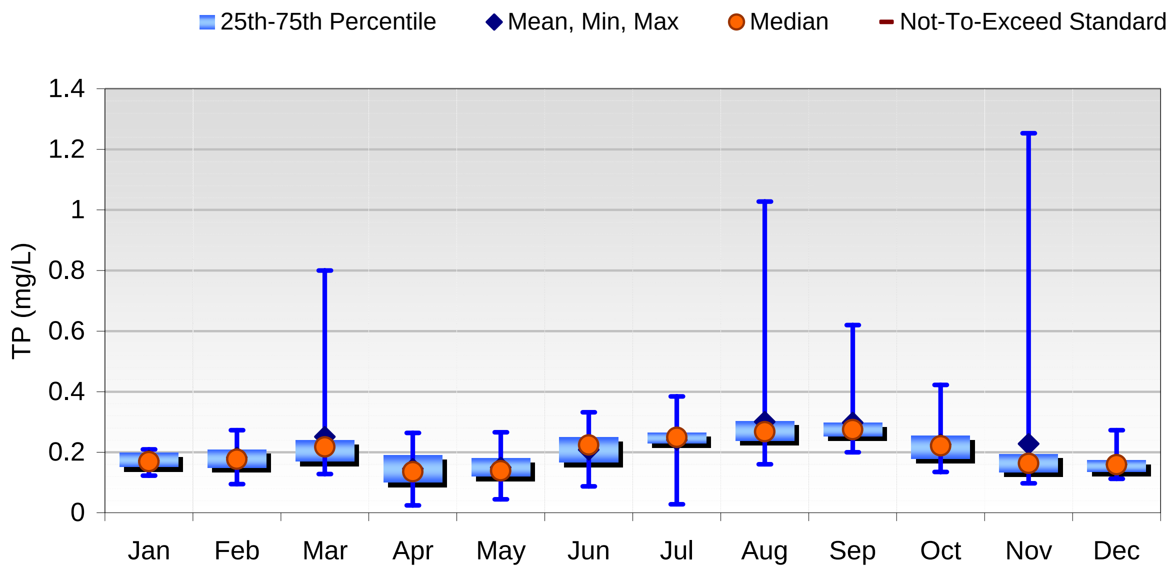


Figure 3-10. Seasonal TP observations for the Vermillion River at the mouth (VM00.1M) over the period June 11, 1991, to September 18, 2002.

The percentage of TP that is dissolved is shown in Figure 3-11 for all dates on which both parameters were sampled at the mouth of the LVR. In general, water quality samples with high proportions of dissolved phosphorus can potentially indicate that sources associated with human or animal wastes (such as from wastewater treatment plants, septic systems, or livestock) are more dominant than sources associated with sheet and rill or streambank erosion. The percentage of TP dissolved in the LVR appears to have declined over time; the overall average is approximately 35 percent.

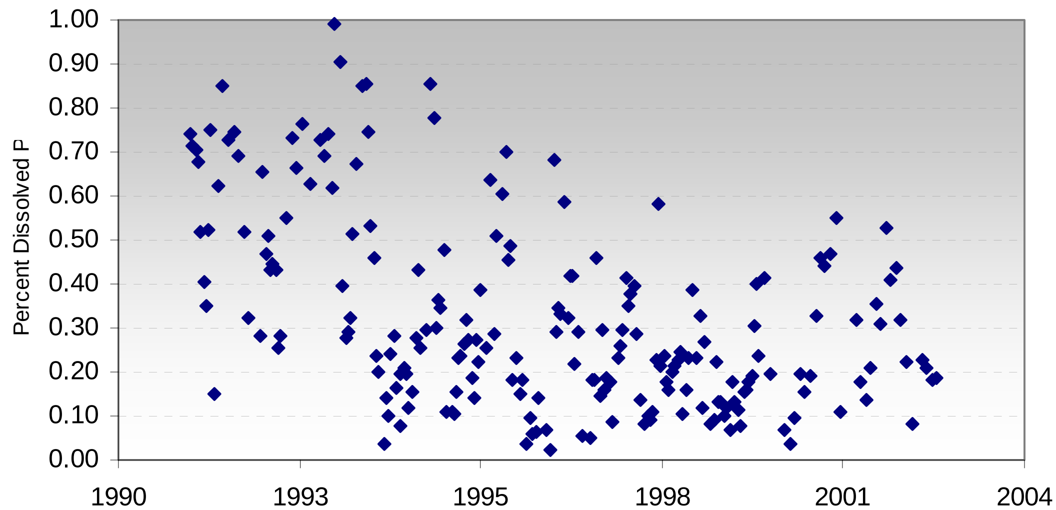


Figure 3-11. Percentage of dissolved phosphorus for the Vermillion River at VM00.1M over the period June 11, 1991, to September 18, 2002.

All the TP data for the Vermillion River at Hastings (station MCCC055) are plotted in Figure 3-12. In general, the concentrations are significantly higher than those observed downstream at the mouth of the LVR. Most samples are between approximately 0.10 mg/L and 1.50 mg/L.

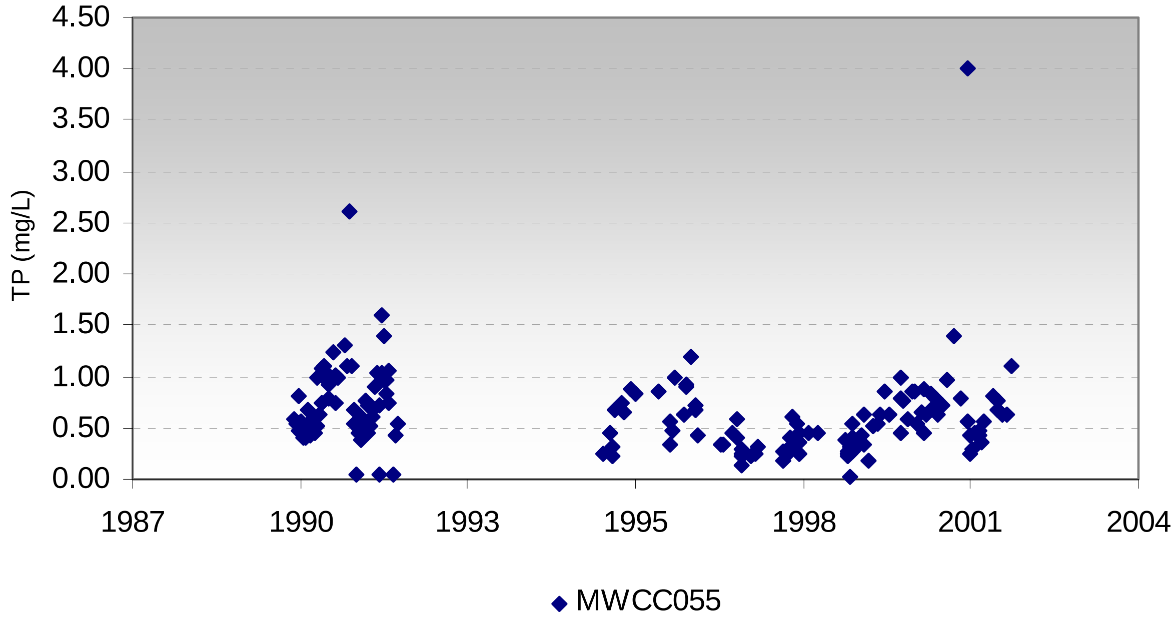


Figure 3-12. All TP observations for the Vermillion River at CR-47 near Hastings (station MWC055) over the period April 6, 1990, to December 20, 2001.

The average monthly TP data for Hastings (MCC055) are shown in Figure 3-13. Average values are highest in January (only two samples, however) and lowest in April. Average and median concentrations tend to increase through the summer months and peak in September.

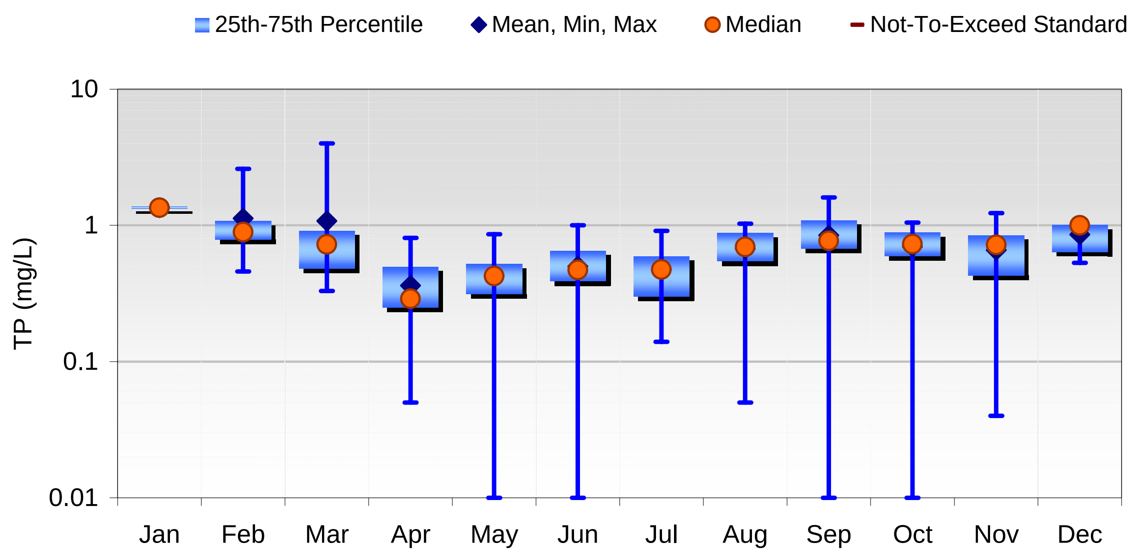


Figure 3-13. Seasonal TP observations for the Vermillion River at CR-47 near Hastings (station MWC055) over the period April 6, 1990, to December 20, 2001.

Flow-weighted TP concentrations for the Vermillion River near Hastings are shown in Figure 3-14. Flow percentiles were determined by generating a flow frequency table, which consisted of ranking all the observed flows associated with a sampling event from the lowest observed flow to the highest. The flows were then grouped into ten equal categories or flow range percentiles. Flow-weighted concentrations were calculated for each flow range percentile by determining a total load for the observations in each flow range and dividing by the total observed flow in the flow range. As Figure 3-14 shows, TP concentrations are highest during low-flows, indicating that a constant source of TP, such as a wastewater treatment plant, is likely dominant. This conclusion is reinforced by Figure 3-15, which shows that a very high proportion of the TP (65 percent) is dissolved. Discharges from the Empire waste water treatment plant (WWTP) are believed to be the cause of these observations and conditions are expected to change when the plant discharge is relocated.

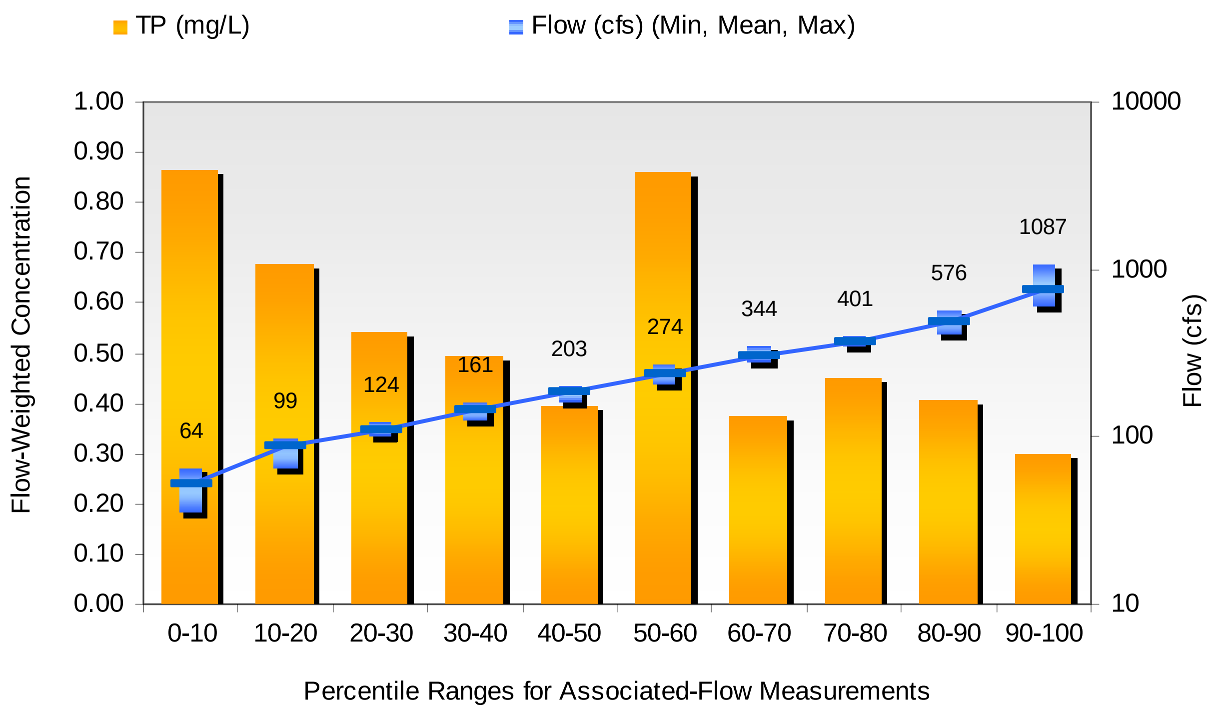


Figure 3-14. Flow-weighted TP concentrations for the Vermillion River at CR-47 near Hastings (station MWC055) over the period April 20, 1995, to December 20, 2001.

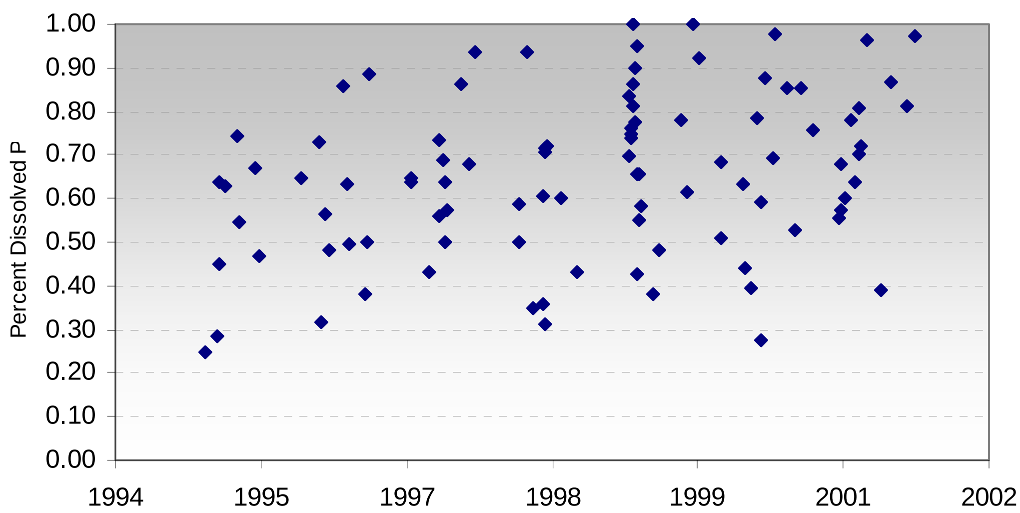


Figure 3-15. Percentage of dissolved phosphorus concentrations for the Vermillion River at CR-47 near Hastings (station MWC055) over the period April 20, 1995, to December 20, 2001.

Note: The percent dissolved phosphorus is believed to be high due to the influence of the Empire WWTP.

The available chlorophyll *a* data for the Vermillion River are shown in Table 3-6. Eight of these stations are on the LVR, and four are on the Upper Vermillion River. More than 90 percent of the observations, however, are for stations on the Upper Vermillion River. The average chlorophyll *a* concentration in the Upper Vermillion River is 46 µg/L, and the average chlorophyll *a* concentration in the LVR is 6 µg/L.

Table 3-6. Summary of Available Chlorophyll *a* Data for the Vermillion River.

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (µg/L)	Average (µg/L)	Maximum (µg/L)
MS221	4/30/1990	9/28/1992	31	12.8	59.58	115
MS295	8/23/1995	9/9/1998	4	4.41	13.67	20.8
MS297	8/23/1995	9/9/1998	4	13.8	24.75	46.9
MS299	8/5/1998	9/9/1998	3	24.2	34.67	52.4
MWCC053	1/23/1985	12/16/1992	220	0.4	5.82	70
MWCC054	1/9/1985	12/16/1992	214	0.7	5.5	28
MWCC055	4/6/1990	12/18/1991	70	1.4	11.23	72
S000-896	6/23/1999	9/4/2001	8	3.2	6.08	11.4
S001-193	7/25/2001	7/25/2001	1	58.4	58.4	58.4
S001-226	5/29/2001	7/25/2001	2	4.17	4.97	5.77
S001-230	7/25/2001	7/25/2001	1	56.6	56.6	56.6
VM00.1M	10/22/1998	5/29/2001	6	0	27.93	62.66

Note: Chlorophyll *a* analyses by spectrophotometry are shown. At VM 100.1M there are 66 additional chlorophyll *a* analyses by fluorometric methods. These are not included as the comparability to spectrophotometric results is uncertain.

All the chlorophyll *a* data for the Vermillion River at Hastings (station MCCC055) are plotted in Figure 3-16. Most values are relatively low, and there does not appear to be a discernible increasing or decreasing trend over time.

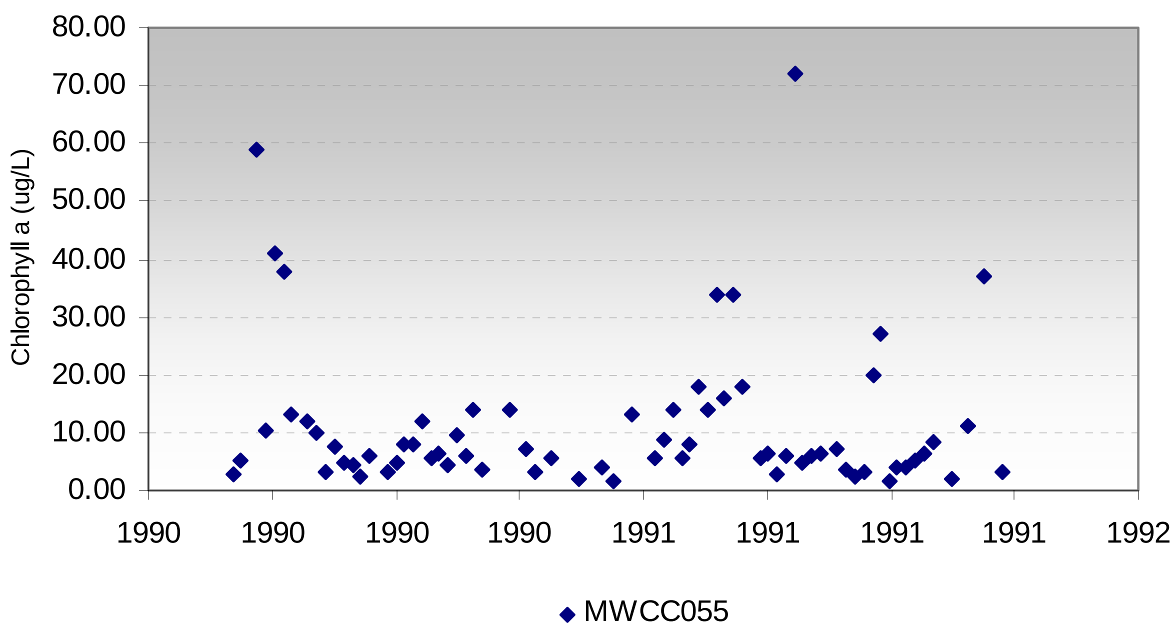


Figure 3-16. All chlorophyll *a* observations for the Vermillion River at CR-47 near Hastings (station MWC055) over the period April 6, 1990, to December 18, 1991.

The average monthly chlorophyll *a* data at Hastings (MCC055) are shown in Figure 3-17. Concentrations increase significantly from January through May, decrease in June, and then remain fairly steady through the rest of year.

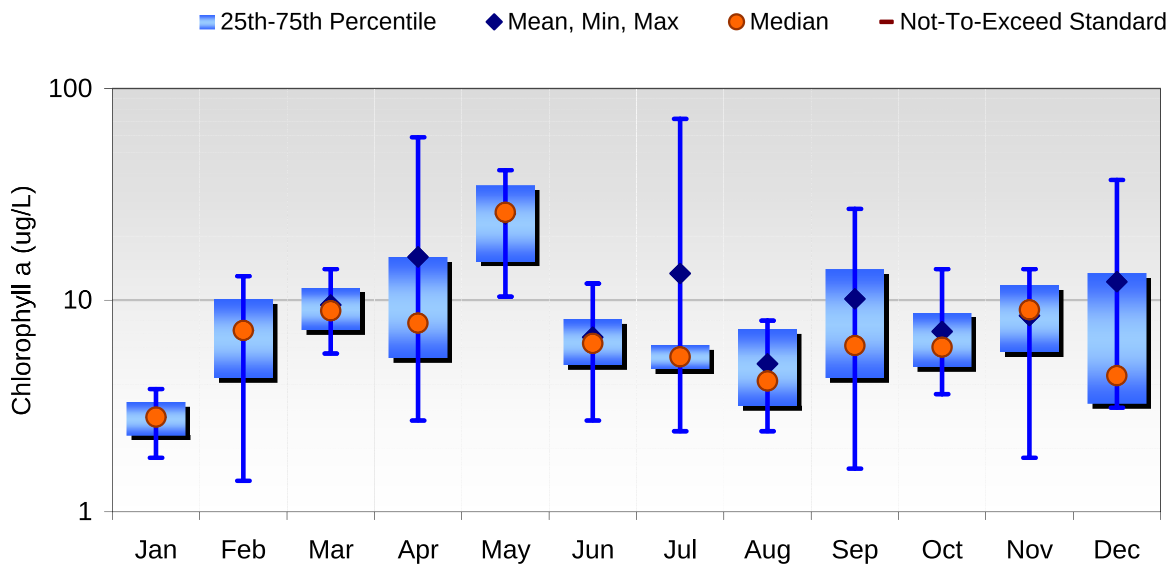


Figure 3-17. Seasonal chlorophyll *a* observations for the Vermillion River at CR-47 near Hastings (station MWC055) over the period April 6, 1990, to December 18, 1991.

3.4.2 Vermillion River Sloughs

Water quality data have been sampled at one location on the Vermillion Slough and one location on the Truedale Slough. Different station ID were assigned to the data in Legacy STORET and modernized STORET and thus the stations are reported as separate stations in Table 3-7. Relatively limited data are available for these two waterbodies.

Table 3-7. Period of Record for Water Quality Stations on Vermillion River Sloughs

Agency Name	Station ID	Station Name	First Date Sampled	Last Date Sampled	Number of Observations (All Parameters)
MPCA	MS296	Vermillion Slough at east bridge, 1 1/8 miles east of Hastings	6/12/1995	9/9/1998	91
MPCA	MS298	Truedale Slough, northeast ¼ Section 5, ¼ mile southeast of Hastings	6/12/1995	9/9/1998	108
MPCA	S001-227	Vermillion Slough at east 4 bridge, 1 1/8 miles east of Hastings	5/29/2001	7/25/2001	25
MPCA	S001-229	Truedale Slough, northeast ¼ Section 5, 5 ¼ miles southeast of Hastings	7/25/2001	7/25/2001	14

The available turbidity data for the Vermillion and Truedale Sloughs are summarized in Table 3-8. There are few data with which to conduct any type of meaningful analysis. Our current understanding is that water quality in the sloughs is essentially representative of its source (either the LVR or Pool 3, depending on the direction of flow). Therefore, Table 3-9 displays the turbidity data for any station in either Pool 3 or the LVR that were collected on the same day turbidity was measured in one of the sloughs. It is difficult to distinguish any particular pattern from these limited data, although it appears that turbidity values in Truedale Slough were comparable to those in the LVR, whereas turbidity in the Vermillion Slough was lower. Also, the turbidity in the Vermillion Slough was significantly less than that in Truedale Slough for the 1998 sampling, but was almost the same for the July 25, 2001, sampling.

Table 3-8. Summary of Available Turbidity Data for the Vermillion River Sloughs

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (NTU or FTU)	Average (NTU or FTU)	Maximum (NTU or FTU)
MS296	8/5/1998	9/9/1998	3	16	17.67	20
MS298	8/5/1998	9/9/1998	3	39	41.67	46
S001-227	5/29/2001	7/25/2001	2	18	19.5	21
S001-229	7/25/2001	7/25/2001	1	22	22	22

Table 3-9. Summary of Available Turbidity Data for the Vermillion River Sloughs, LVR, and Mississippi River Pool 3

Date	Pool 3	Vermillion Slough		Truedale Slough		LVR						
	483027	MS296	S001-227	S001-229	MS298	MS299	S001-193	S001-226	MS297	S001-230	VM00_1M	MS295
8/5/1998	29.6	16			40	32			41		38	19
8/18/1998		20			39	37			30			15
9/9/1998		17			46	39			45			9
7/25/2001			21	21.75			37.25	8.9		29		

The TSS, TP, and chlorophyll *a* data for the Vermillion and Truedale Sloughs are summarized in Table 3-10 to Table 3-12. Very few data are available.

Table 3-10. Summary of Available TSS Data for the Vermillion River Sloughs

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)
MS298	7/13/1995	8/23/1995	2	46	58	70
S001-227	5/29/2001	7/25/2001	2	27	35.5	44
S001-229	7/25/2001	7/25/2001	1	30	30	30

Table 3-11. Summary of Available TP Data for the Vermillion River Sloughs

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)
MS296	7/13/1995	9/9/1998	5	0.25	0.32	0.4
MS298	7/13/1995	9/9/1998	5	0.23	0.28	0.33

Table 3-12. Summary of Available Chlorophyll *a* Data for the Vermillion River Sloughs

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (μg/L)	Average (μg/L)	Maximum (μg/L)
MS296	8/5/1998	9/9/1998	3	5.45	8.66	14.6
MS298	8/5/1998	9/9/1998	3	24.2	33.37	43.9
S001-227	5/29/2001	5/29/2001	1	17.4	17.4	17.4

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (µg/L)	Average (µg/L)	Maximum (µg/L)
S001-229	7/25/2001	7/25/2001	1	33	33	33

3.4.3 Off-Channel and On-Channel Lakes

A number of lakes are found in the LVR system. For purposes of TMDL development, these lakes have been categorized as off-channel or on-channel lakes, based partly on a memo submitted by MPCA to MNDNR (Heiskary, 1999) and partly on our own observations.

On-channel Lakes
Larson Lake
Goose Lake
Wildcat Lake
Birch Lake

Off-channel Lakes
Spring Banks Lake
Rattling Springs Lake
Nelson Lake
Clear Lake
Mud Hen Lake
Sharp Muskrat Lake
North Lake
Jones Lake

Because the Minnesota listing process does not account for turbidity in lakes, the in-channel lakes are not officially listed as impaired. The lakes will, however, be analyzed for their potential contribution of loading to the LVR or to provide perspective on LVR conditions.

The available data for the off-channel and on-channel lakes are summarized in Table 3-13 to Table 3-18. The data are somewhat limited. It appears, however, that there are some significant differences between the off-channel and on-channel lakes. For example, Upper and Lower Rattling Springs lakes have very high Secchi disk depths, whereas the on-channel and larger backwater lakes (Goose, Clear, Larson, and Birch) have an average Secchi depth of approximately 0.4 meter. The on-channel lakes also have higher chlorophyll *a* values and there appears to be an increasing trend in chlorophyll *a* moving from upstream to downstream. In general, the observed chlorophyll a values in the on-channel lakes (approximately 80 µg/L) is significantly higher than the Vermillion River at Hastings (approximately 6 µg/L).

Despite the unusually clear water in the off-channel lakes, the phosphorus and chlorophyll *a* concentrations are high. Although Wildcat Lake is connected to the Vermillion system during high water periods and receives high amounts of sediment and nutrients like the other lakes, there is a clear difference in its clarity. One theory is that there are significant groundwater inputs into these lakes, which are near the bluffs. MNDNR measured discharge from Lower Rattling Springs to the Vermillion River during low-flow conditions at 1.45 cfs, indicating that groundwater was supplying the lake. Further information from MNDNR indicates that the sediment structure of lakes close to the bluffs could be very different from that of the lakes directly connected to the river. MNDNR's field notes state that the department has observed higher amounts of cobble and sand in several lakes near the bluffs. Other field notes and reports from MNDNR and the U.S. Fish and Wildlife Service (USFWS) indicate that the Vermillion and Mississippi systems in this area have sediments dominated by silt and clay.

Table 3-13. Period of Record for Water Quality Stations on Off-Channel and On-Channel Lakes

Agency Name	Station ID	Station Name	First Date Sampled	Last Date Sampled	Number of Observations (All Parameters)
MPCA	25-0005	Lake Goose 6 miles northwest of Red Wing	6/12/1995	9/9/1998	161
MPCA	25-0007	Lake Wildcat 5.5 miles northwest of Red Wing	6/12/1995	7/25/2001	147
MPCA	25-0009	Lake Birch 5 miles northwest of Red Wing	6/12/1995	9/9/1998	140
MPCA	25-0016	Lake Larson 7 miles northwest of Red Wing	6/12/1995	7/25/2001	168
MPCA	25-0019	Lake Clear 9.5 miles northwest of Redwing	6/12/1995	9/9/1998	171
MPCA	25-0021	Lake Little Rattling Springs 8.5 miles northwest of Red Wing	6/12/1995	9/9/1998	100
Prairie Island Indian Community	CL1	Clear Lake	6/6/2001	9/19/2001	10
Prairie Island Indian Community	NL1	North Lake Upper	6/6/2001	9/19/2001	44
Prairie Island Indian Community	NL2	North Lake Upper	6/6/2001	9/19/2001	44
USGS	443753092400401	Nelson Lake, south end (Section W5) at Prairie Island	9/20/1994	4/30/1996	168

Table 3-14. Summary of Available TSS Data for Off-Channel and On-Channel Lakes

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)
25-0005	6/12/1995	8/23/1995	3	20	24	26
25-0007	6/12/1995	7/25/2001	3	20	43	79
25-0009	6/12/1995	8/23/1995	3	27	54	82
25-0016	6/12/1995	7/25/2001	4	28	51	70
25-0019	6/12/1995	8/23/1995	3	17	27	45
25-0021	6/12/1995	6/12/1995	1	23	23	23

Table 3-15. Summary of Available Turbidity Data for Off-Channel and On-Channel Lakes

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (NTU)	Average (NTU)	Maximum (NTU)
25-0007	8/5/1998	7/25/2001	2	54	60.5	67
25-0016	8/5/1998	7/25/2001	2	34	38	42

Table 3-16. Summary of Available Secchi Disk Depth Data for Off-Channel and On-Channel Lakes

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (m)	Average (m)	Maximum (m)
25-0005	6/12/1995	8/5/1998	5	0.14	0.38	0.55
25-0007	6/12/1995	8/5/1998	5	0.15	4.87	23
25-0009	6/12/1995	8/5/1998	5	0.2	0.28	0.45
25-0016	6/12/1995	8/5/1998	5	0.2	0.34	0.55
25-0019	6/12/1995	9/9/1998	7	0.24	0.45	0.85
25-0021	6/12/1995	9/9/1998	4	0.15	7.20	28
NL1	6/6/2001	9/19/2001	11	0.25	0.35	0.5
NL2	6/6/2001	9/19/2001	11	0.25	0.34	0.5

Table 3-17. Summary of Available TP Data for Off-Channel and On-Channel Lakes

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)
25-0005	6/12/1995	9/9/1998	7	0.17	0.40	0.69
25-0007	6/12/1995	9/9/1998	7	0.16	0.42	0.87
25-0009	6/12/1995	9/9/1998	7	0.18	0.30	0.37
25-0016	6/12/1995	9/9/1998	8	0.17	0.27	0.36
25-0019	6/12/1995	9/9/1998	7	0.1	0.21	0.27
25-0021	6/12/1995	9/9/1998	5	0.17	0.21	0.25
443753092400401	9/20/1994	4/30/1996	3	0.17	0.29	0.47
CL1	6/6/2001	9/19/2001	5	0.125	0.20	0.327
NL1	6/6/2001	9/19/2001	11	0.104	0.18	0.225
NL2	6/6/2001	9/19/2001	11	0.105	0.19	0.28

Table 3-18. Summary of Available Chlorophyll *a* Data for Off-Channel and On-Channel Lakes

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (μg/L)	Average (μg/L)	Maximum (μg/L)
25-0005	6/12/1995	9/9/1998	6	40.1	108.67	173
25-0007	6/12/1995	7/25/2001	7	35.2	111.77	291
25-0009	6/12/1995	9/9/1998	6	41.3	68.12	135
25-0016	6/12/1995	7/25/2001	8	16	49.48	68.9
25-0019	6/12/1995	9/9/1998	6	32.6	82.75	165
25-0021	6/12/1995	9/9/1998	4	3.2	32.60	111
CL1	6/6/2001	9/19/2001	5	7.5	24.10	41
NL1	6/6/2001	9/19/2001	11	7.9	28.45	55
NL2	6/6/2001	9/19/2001	11	8.3	43.48	74

3.4.4 Mississippi River

Available water quality data for the Mississippi River were retrieved and analyzed because of the interconnection between Pool 3 and the LVR. The period of record at select Mississippi River stations is shown in Table 3-19. A relatively good data set is available, although sampling efforts have decreased in intensity over the past several years.

Table 3-19. Period of Record at Select Mississippi River Stations

Agency Name	Station ID	Station Name	First Date Sampled	Last Date Sampled	Number of Observations (All Parameters)
Met Council	MWCC035	Mississippi River Above Lock and Dam No 3	1/9/1985	12/16/1992	4247
MPCA	045	Mississippi Rive near Prairie Island	6/19/1974	3/1/1977	1183
MPCA	MS301	Mississippi River downstream of Hastings bridge	5/24/1995	5/24/1995	4
MPCA	MSU-797-BB15E67	Mississippi River Lock and Dam 3 5 miles northwest of Red Wing	6/28/1967	8/5/1992	1058
MPCA	S000-068	Mississippi River at Lock and Dam 3 at Hastings	10/4/1999	9/9/2002	200
USACE	UM796.9	Lock and Dam 3Lock and Dam	6/6/1994	11/27/1996	734
USACE	UM815.6	Lock and Dam 2Lock and Dam	6/6/1994	11/18/1996	129
USGS	05331580	Mississippi River below Lock and Dam 2 at Hastings	1/1/1936	7/26/2002	14180
USGS	05344980	Mississippi River at Lock and Dam, 3 near Red Wing	7/1/1969	9/8/1981	5172
WDNR	483027	Mississippi River Lock and Dam 3 near Red Wing	1/19/1977	7/12/2001	8708
WDNR	483058	Mississippi River at Pool 3 Comp. Sed.	6/14/1994	6/14/1994	64

Table 3-20 summarizes the available turbidity data for select Mississippi River stations. Only four stations have turbidity data.

Table 3-20. Summary of Available Turbidity Data for Select Mississippi River Stations

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (NTU)	Average (NTU)	Maximum (NTU/L)
05331580	10/2/1995	9/10/1996	5	3.9	16.78	26
483027	2/7/1991	12/1/1998	98	1.4	14.24	52.8
S000-068	10/4/1999	6/10/2002	17	2.1	23.15	51
MR796.9	1/11/1979	12/17/2002	974	1	12.73	80

Table 3-21 summarizes the available TSS data for Mississippi River stations. The average TSS concentration for all Pool 3 stations is approximately 30 mg/L. As discussed below, the average TSS in Pool 3 is significantly less than that observed in the Upper Vermillion River at Hastings.

Table 3-21. Summary of Available TSS or SSC Data for Select Mississippi River Stations

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)
045	6/19/1974	3/1/1977	34	0.5	11.15	46
05331580	11/28/1972	7/26/2002	125	1	40.06	187
05344980	12/11/1969	9/29/1977	58	0	23.16	92
483027	1/19/1977	12/1/1998	267	0	29.4	138
MSU-797-BB15E67	6/28/1967	7/8/1992	34	1.2	31.46	140
MWCC035	1/9/1985	12/16/1992	189	1	25.48	129
S000-068	10/22/2001	9/9/2002	10	2.8	32.12	71
UM796.9	6/6/1994	11/27/1996	366	0.8	31.94	160.8
UM815.6	6/6/1994	11/18/1996	64	1.9	44.17	137.1

All the TSS data for the Mississippi River below Lock and Dam 2 are shown in Figure 3-18. There is a significant gap in data between 1976 and 1995, but the concentrations for the two time periods are relatively similar.

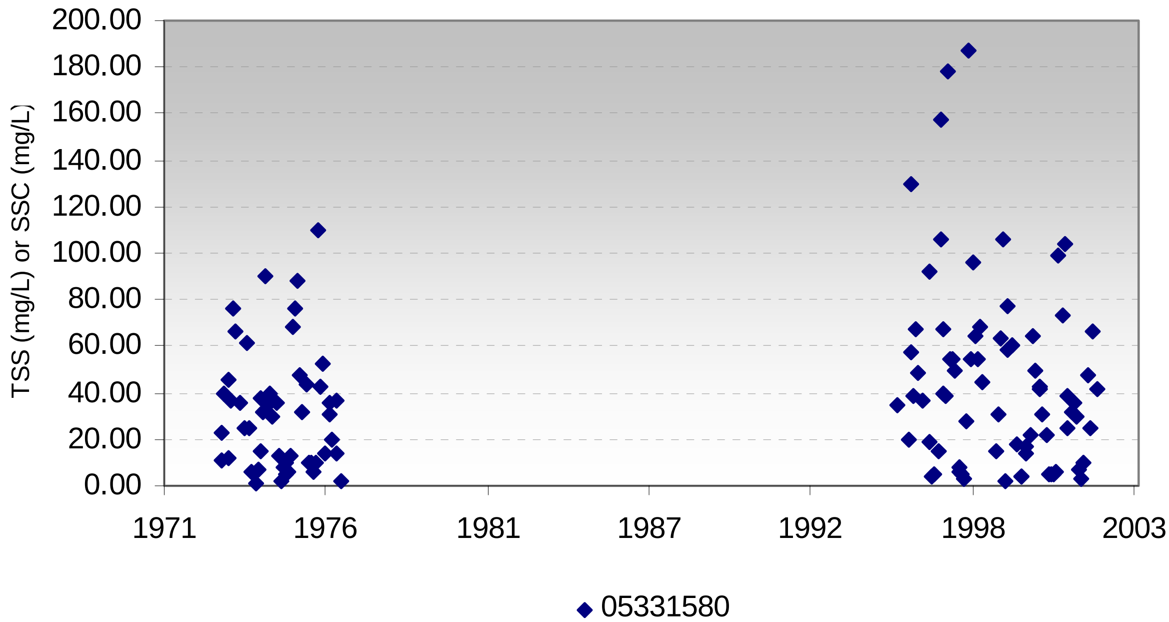


Figure 3-18. All TSS or SSC observations at the Mississippi River below Lock and Dam 2 at Hastings. TSS data were collected between November 28, 1972, and December 21, 1976, and SSC data were collected between October 31, 1995, and July 26, 2002.

Seasonal TSS data for the Mississippi River below Lock and Dam 2 is plotted in Figure 3-19. Concentrations increase from January through April and then begin a slow decline through the rest of the year.

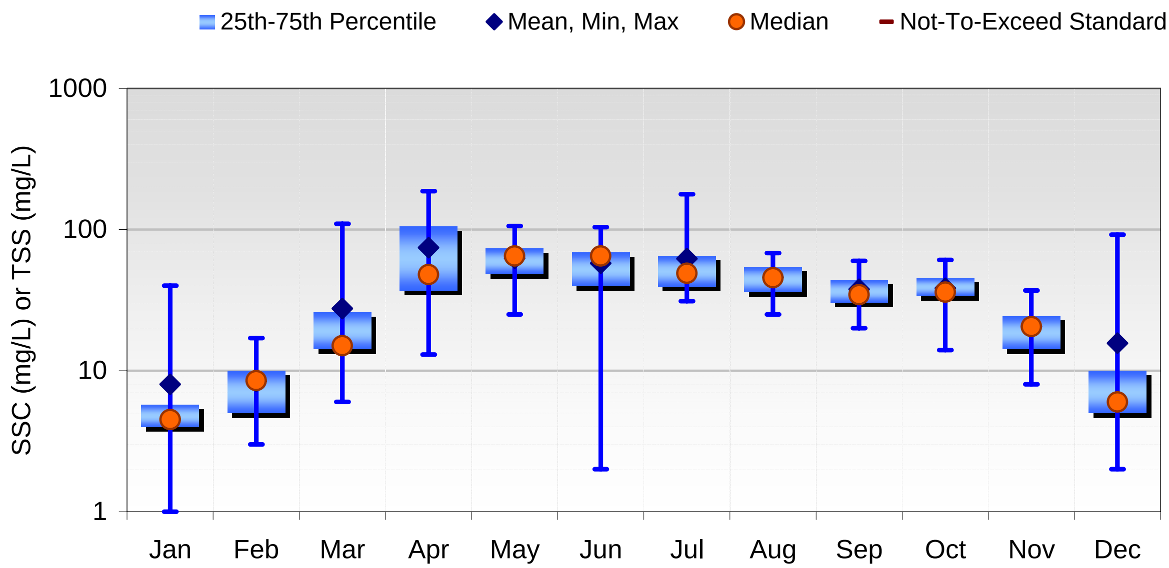


Figure 3-19. Seasonal TSS or SSC observations at the Mississippi River below Lock and Dam 2 at Hastings. TSS data were collected between November 28, 1972, and December 21, 1976, and SSC data were collected between October 31, 1995, and July 26, 2002.

The available TP data for select Mississippi River stations are summarized in Table 3-22. Quite a few data are available, and they indicate that the average TP concentration in Pool 3 is 0.20 mg/L. As discussed further below, TP concentrations in Pool 3 are consistently lower than those observed at the Upper Vermillion River at Hastings.

Table 3-22. Summary of Available TP Data for Select Mississippi River Stations

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)
045	6/19/1974	3/1/1977	34	0.48	1.58	3.28
05331580	11/1/1967	7/26/2002	93	0.05	0.23	0.82
05344980	7/29/1969	4/17/1974	34	0.05	0.3	0.88
483027	1/19/1977	12/1/1998	266	0.09	0.18	0.38
MSU-797-BB15E67	6/28/1967	7/8/1992	34	0.1	0.27	0.55
MWCC035	1/9/1985	12/16/1992	218	0.03	0.22	4.6

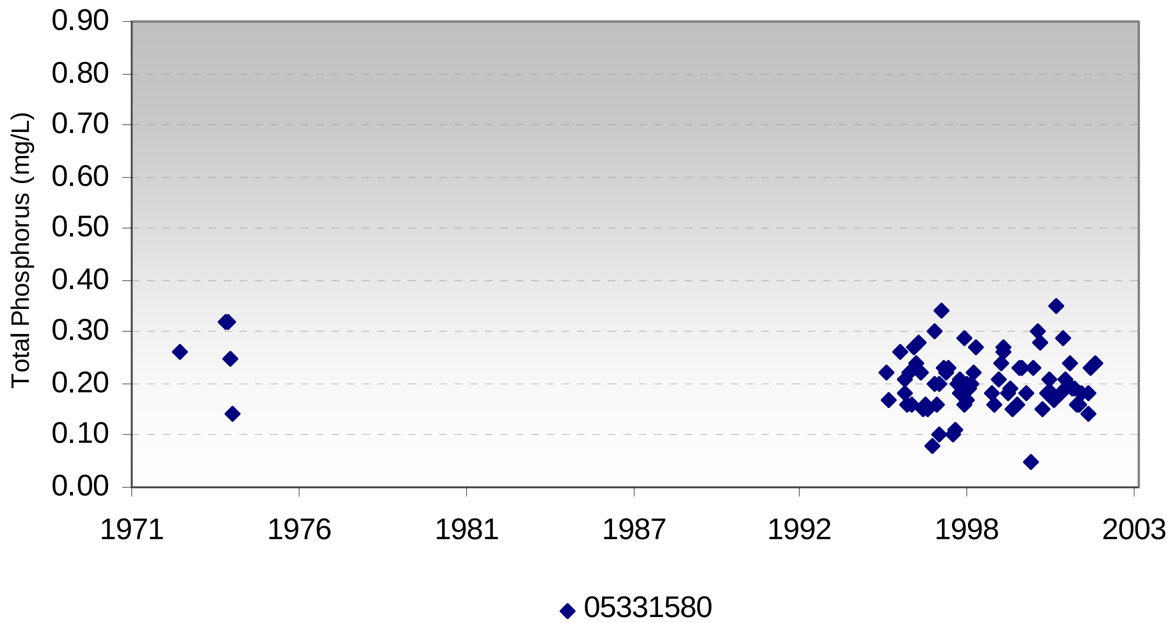


Figure 3-20. All TP observations for the Mississippi River below Lock and Dam 2 at Hastings. Data cover the period November 1, 1967, to July 26, 2002.

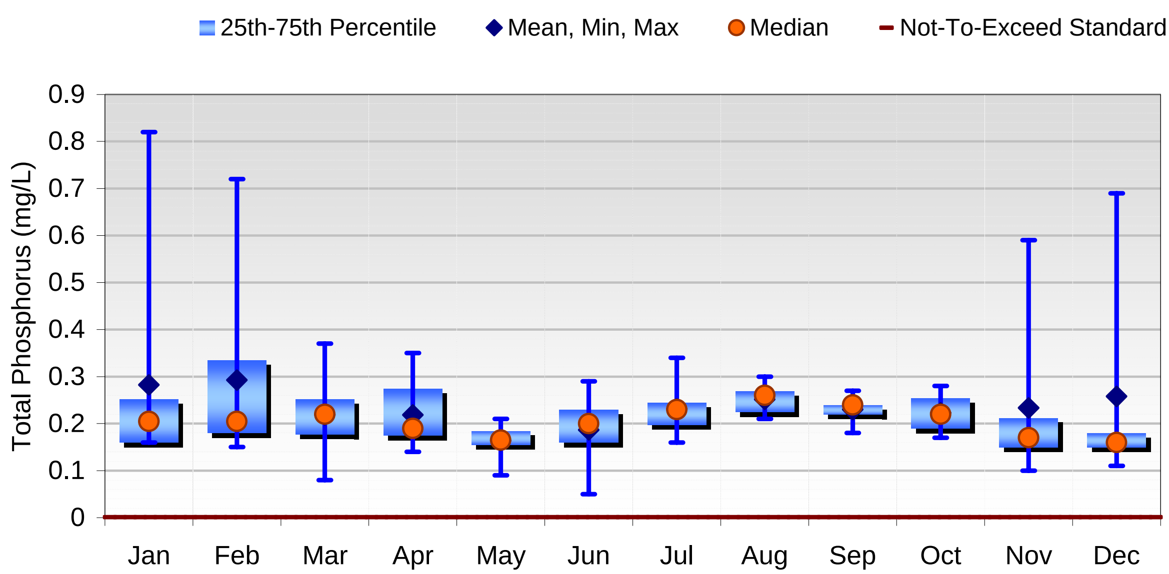


Figure 3-21. Seasonal TP observations for the Mississippi River below Lock and Dam 2 at Hastings. Data cover the period November 1, 1967, to July 26, 2002.

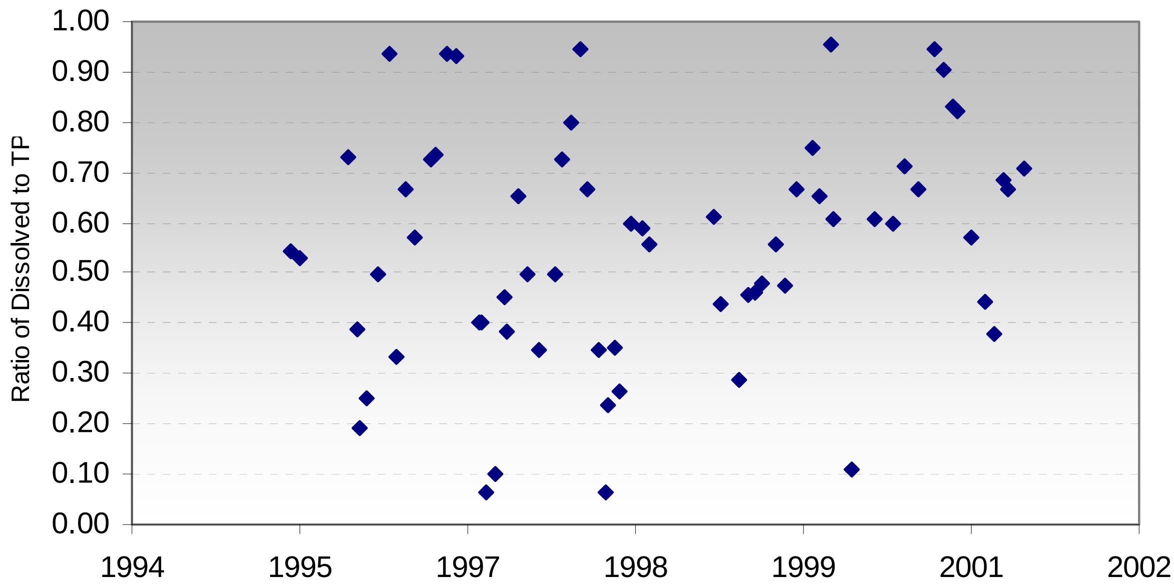


Figure 3-22. Ratio of dissolved phosphorus to total phosphorus at the Mississippi River below Lock and Dam 2 over the period November 1, 1967, to July 26, 2002.

Table 3-23. Summary of Available Chlorophyll *a* Data for Select Mississippi River Stations

Station ID	First Date Sampled	Last Date Sampled	Number of Observations	Minimum (μg/L)	Average (μg/L)	Maximum (μg/L)
483027	7/6/1988	12/1/1998	194	0.59	28.36	135
MSU-797-BB15E67	6/4/1991	7/8/1992	14	3.2	37.27	99.3
MWCC035	1/9/1985	12/16/1992	215	0.7	39.7	210
S000-068	6/10/2002	9/9/2002	4	21.5	28.35	34.4

3.5 Review of Available Biological Data

3.5.1 Background

The effects of increased turbidity and sedimentation on the biota begin at the primary trophic level (Henley, 2000). High turbidity levels can limit light penetration through the water column, thereby limiting macrophyte growth and causing a decline in the density of submerged aquatic vegetation. From that point on, a detrimental cascade of effects can be observed through the rest of the food chain. With reduced macrophyte populations, fewer herbivorous fish and invertebrates can be sustained (Henley, 2000). These impacts can occur at relatively low levels of turbidity. Lloyd et al. (1987) found that an increase in turbidity of 5 NTU decreased primary production by 3 to 13 percent while a 25 NTU increase decreased primary productivity by up to 50 percent.

Increased turbidity can also have direct effects on higher-level organisms. Increased turbidity has been found to decrease oxygen levels as well as mechanically interfere with the uptake of oxygen by gill epithelium (Henley, 2000, Waters, 1995).

Habitat degradation can be another negative effect of turbidity and sedimentation. If turbidity limits macrophytes growth, streambanks and riverbanks become unstable and susceptible to erosion. This, in itself, can become another source of turbidity (Allen, 1995). Moreover, reduced macrophyte density can reduce essential fish spawning habitat. The problem is compounded when sediment particles fall from the water column into the sediment. Loose, unstable sediment is not suitable for many species of fish eggs and cannot support many populations of macroinvertebrates. Interstitial spaces in coarse sediment can be filled with the invading silt, eliminating macroinvertebrate habitat (Lenat, 1981).

3.5.2 Available Data

A variety of agencies were contacted in an attempt to compile biological data during Phase I activities. Table 3-24 provides a list of the data already obtained or requested.

Table 3-24. Biological Data Obtained and Requested

Source of Data	Years	Status
Lower Vermillion System		
MNDNR electrofishing data	1995—2000, some 2002	In possession
MNDNR seine data	1995–2002	In possession
MNDNR macrophyte data		Requested
MPCA phytoplankton count	1995	In possession
Mississippi River Pool 3		
MNDNR electrofishing data	1993, 1995–2000, some 2002	In possession
MNDNR seine data	1993–2002	In possession
USFWS fish survey	1996–2001	In possession
MNDNR/Prairie Island Nuclear Plant Fish Survey	1971–present	Requested

Phytoplankton count data were available for Clear, Goose, and Birch lakes in the LVR system. MPCA conducted counts in June and August 1995 for Clear and Goose lakes; counts for Birch Lake were available for only August 1995. The data are summarized and broken down into appropriate classes: green algae, blue-green algae (cyanobacteria), and diatoms. The results are shown in Figure 3-23. The actual numbers of the different classes (as measured in number per milliliter) are estimates from a fast count survey. The data are best suited for use as a snapshot of the overall abundance of each class.

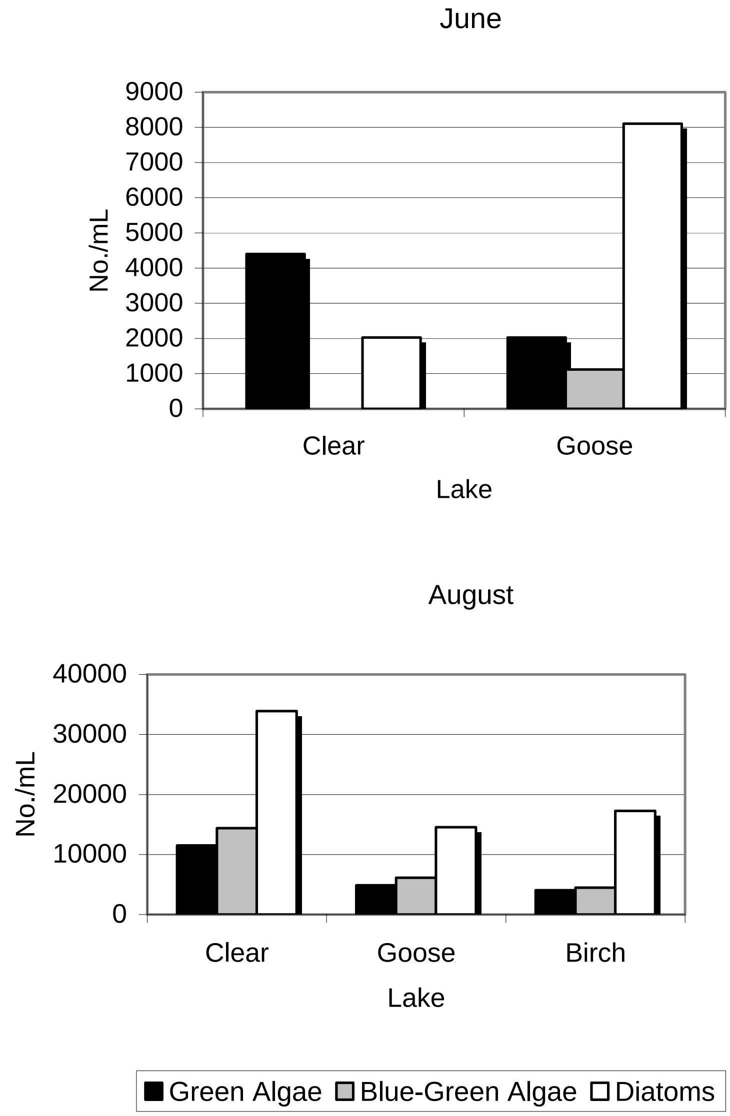


Figure 3-23. Phytoplankton counts for several lakes in the Lower Vermillion River system. MPCA staff collected the data in 1995.

Diatoms are the dominant phytoplankton in most of the samples. This is typical of many riverine systems, including the Upper Mississippi Basin (Baker and Baker; 1979 and Allen, 1995). Diatoms usually play a lesser role in phytoplankton composition in lakes. This is because, without mixing action, diatoms tend to fall out of the water column and settle in the sediment. The mixing action of the river can allow the diatoms to remain suspended in the water column. In a system like the Vermillion River, where streambank scouring could be an issue, resuspension of diatoms from the sediment is certainly a possibility. The large number of diatoms found in MPCA's samples from these lakes indicates that the Vermillion River could heavily influence the samples phytoplankton composition. In Addition, sustained winds and possibly even rough fish movements can aid in mixing and resuspension within the lakes.

Another important factor is the relative abundances of green algae compared to blue-green algae. In the June samples, greens are more dominant than blue-greens. Later in the summer, however, blue-greens are more dominant than greens. Spring green algae dominance followed by later summer blue-green dominance is typical in many eutrophic lakes (Bronmark and Hansson, 1998; Fogg, 1987).

MNDNR has collected aquatic vegetation data for the Vermillion River system for the period from 1995 through 2001 and for 2003. MNDNR reports indicate that much of the system is devoid of any aquatic vegetation. When vegetation is present, biodiversity is low and the species present are considered common. Some species present, such as curly pondweed (*Potamogeton crispus)*, are even considered "ecologically invasive" (Hoffman, 1997). Notable exceptions include sightings of horned pondweed (*Zannichellia palustris*), which is endangered in Indiana and rare in northeastern states. Wild rice (*Zizania aquatica*) was also noted in some of the more off-channel lakes.

MNDNR has also used these aquatic plant data in the development of an "Aquatic Habitat Quality Index Summary." This index is based on a qualitative assessment of aquatic vegetation diversity and density, bathymetric diversity, substrate composition, and water quality. Index values calculated for the Vermillion River system indicate that the majority of the system is characterized as fair to poor. On-channel lakes such as Larson and Birch, as well as large backwater lakes like Clear and Goose, consistently scored in the poor to very poor range. In contrast, Rattling Springs and Jones Lakes, two smaller, off-channel waterbodies close to the bluffs, consistently scored in the good range.

MNDNR collected fisheries survey data in the LVR system from 1995 to 2000 and in 2002. The data were collected by either the seining or electrofishing method. Electrofishing was conducted with the intent of monitoring some of the important game-fish species known to occur in the system and comparing their populations from year to year. These year to year data are best summarized with a catch per unit effort (CPUE).

Electrofishing data from the Mississippi River Pool 3 were used as a comparison to the Vermillion electrofishing data. Figure 3-24 shows the CPUE for some of the major game-fish species, namely, bluegill (*Lepomis macrochirus*), largemouth bass (*Micropterus salmoides*), and black and white crappie (*Pomoxis nigromaculatus* and *P. annularis*).

CPUE rates were consistently higher in the Lower Vermillion than in the Mississippi. The results indicate that these particular game-fish populations in the Vermillion River are generally healthy. This conclusion is supported by an MNDNR report, which states, "Fish populations are generally healthy and appear stable. This is significant, considering that suspended solids within the water column reduce Secchi readings to less than one foot throughout most of the open-water period" (Dieterman, 2002). The data, as well as the MNDNR report, offer surprising results: despite poor water quality in the system, some game-fish populations appear healthy.

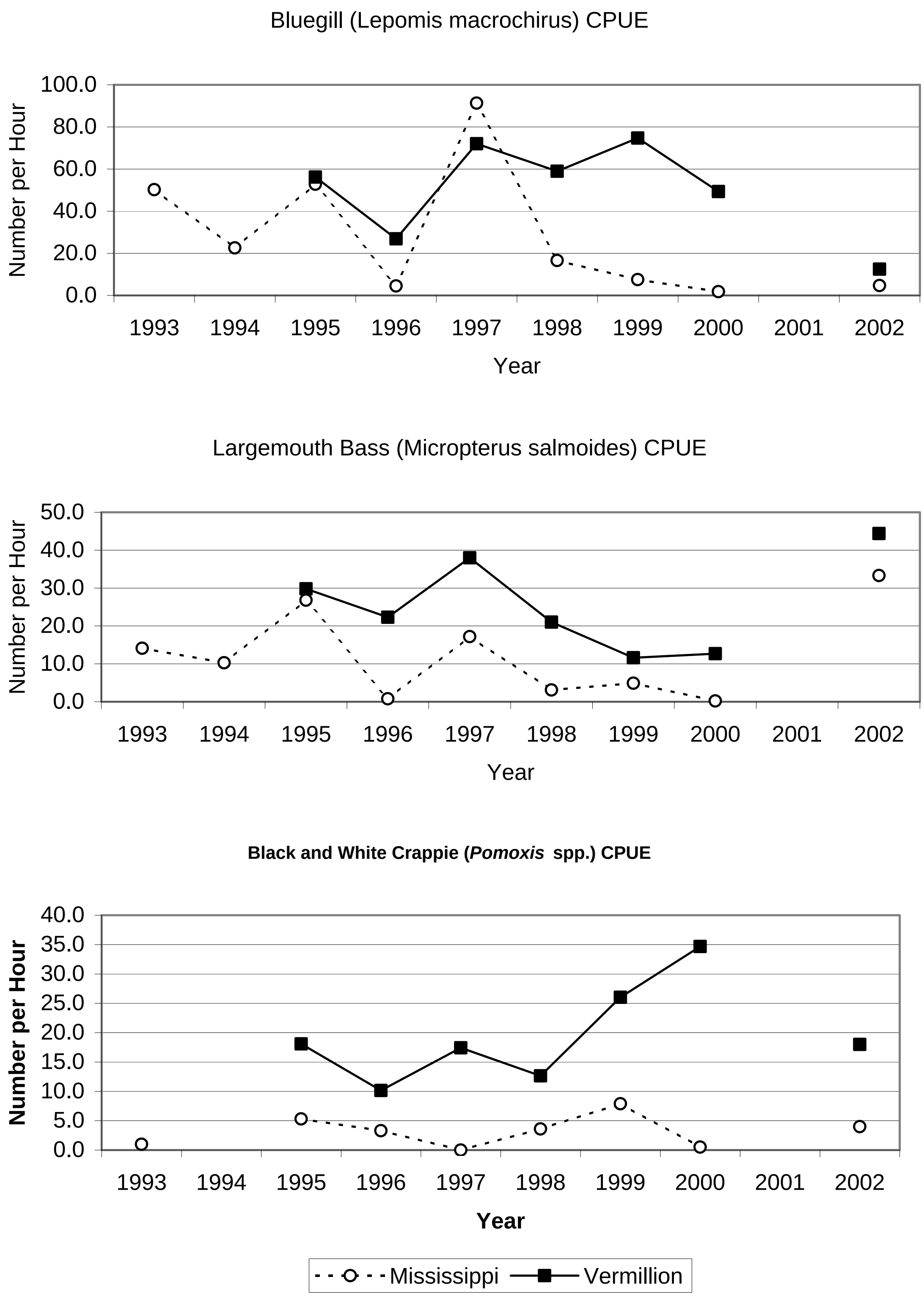


Figure 3-24. Catch per unit effort rates for the LVR system compared with rates from Mississippi River Pool 3. Because, only one electrofishing run was completed in 1997, data are not as accurate as other years. Data for the Vermillion River were not available before 1995. Data were not available for either river in 2001.

3.5.3 Discussion

Although some fish species in the LVR seem to be in good health, qualitative evidence suggests that high turbidity levels might be affecting other species in the LVR. During his long tenure at the Lake City DNR, Dan Deiterman has had many conversations with local people who live on the Vermillion system. Conversations with a former Clear Lake resort owner indicated that the water in the lake was once much clearer in the lake than it is now. Aquatic vegetation was more abundant, and anglers in the area reported catching fair amounts of yellow perch. Yellow perch are now found only in very small numbers in the Vermillion system. Research has shown that yellow perch are more susceptible to negative effects from turbidity and sedimentation than some other game-fish species (Newcomb et al., 1996).

In summary, data with which to fully characterize the current health or trends of the LVR aquatic communities are sufficient. Furthermore, aquatic health is affected by a variety of factors other than water quality and habitat, such as immigration/emigration, intra- and interspecific competition, and predation. The data do suggest, however, that the Vermillion River and its associated lakes are supporting fair populations of game-fish species. In addition, there appear to be some pieces of excellent aquatic life habitat within a system that is poor overall. Additional sampling of all aquatic life variables, especially macroinvertebrates (for which data was not available), would be helpful in understanding the system. Moreover, it would be good to continue identifying the essential high-quality pieces of habitat with the intention of preservation.

4 CONCEPTUAL MODEL OF THE LVR WATERSHED

4.1 LVR Hydrology

The LVR system is hydrologically complex. The Lower Vermillion occupies the floodplain of the Mississippi River and has a naturally low gradient. Flow enters this system from the Upper Vermillion at Hastings, Minnesota; via local tributaries, through movement of groundwater; and by interflow with the Mississippi. The last component is particularly important to understanding the LVR. Because of the operation of Mississippi Lock and Dam 3 for navigation, normal pool in Mississippi Pool 3 is typically greater than 5 feet above the water surface elevation in the LVR. This creates a tendency for water from the Mississippi to flow into the LVR, seeking steeper gradient to the channel below Lock and Dam 3. It also creates a positive groundwater gradient from the Mississippi to the LVR. Finally, because of its own low channel gradient, flow within the LVR can be affected by the water surface elevation at its confluence with the Mississippi, below Lock and Dam 3, and by flows in the Cannon River.

4.1.1 Flow from the Upper Vermillion River

Flows in the Upper Vermillion River at Hastings form the upstream boundary condition for analysis of the hydrology of the LVR. This section summarizes the available flow data, which appear to be in good shape after 1994. To capture earlier years, a regression methodology is developed to relate flows below Hastings to continuous gaging conducted by USGS upstream at Empire, Minnesota.

4.1.1.1 Flow Gages on the Upper Vermillion River

USGS has gaged flow at two locations on the mainstem of the Upper Vermillion River. Figure 4-1 shows the site station map for gage 05345000 (Vermillion River near Empire), and Figure 4-2 shows gage 05346000 (Vermillion River at Hastings). USGS has collected data intermittently at both gages since 1942 but last gaged flow at Hastings in 1990. The USGS Hastings gage was upstream of Vermillion Street, to the southwest of town. In 1994 MCES, through Dakota County Soil and Water Conservation District, established a new gage (213567) inside the ConAgra Mill at 2005 Vermillion Street near Highway 61 in Hastings, southeast of the center of town (Figure 4-3). This gage captures a significantly larger drainage area than the former USGS gage and has a calibrated rating curve maintained by MCES staff and cooperating agencies. Station information and periods of record for each gage are summarized in 0.

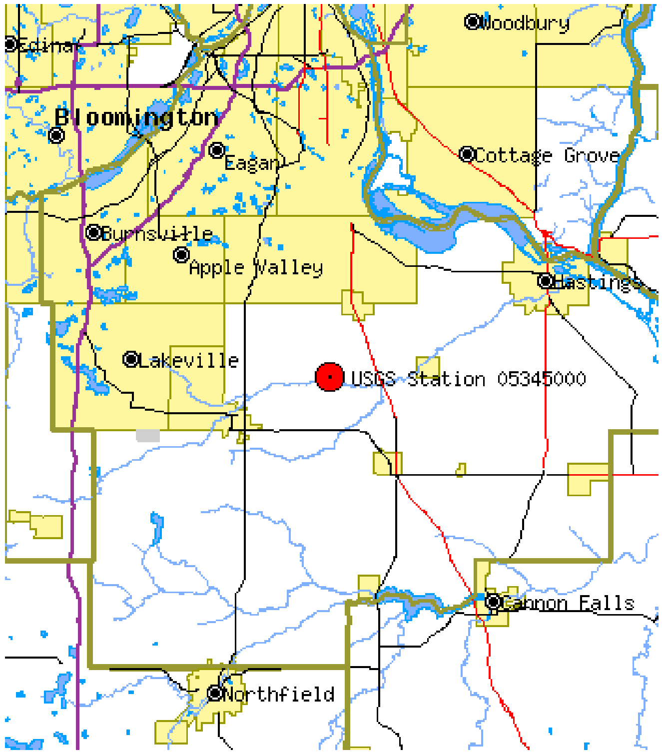


Figure 4-1. Site station map for USGS gage 05345000.

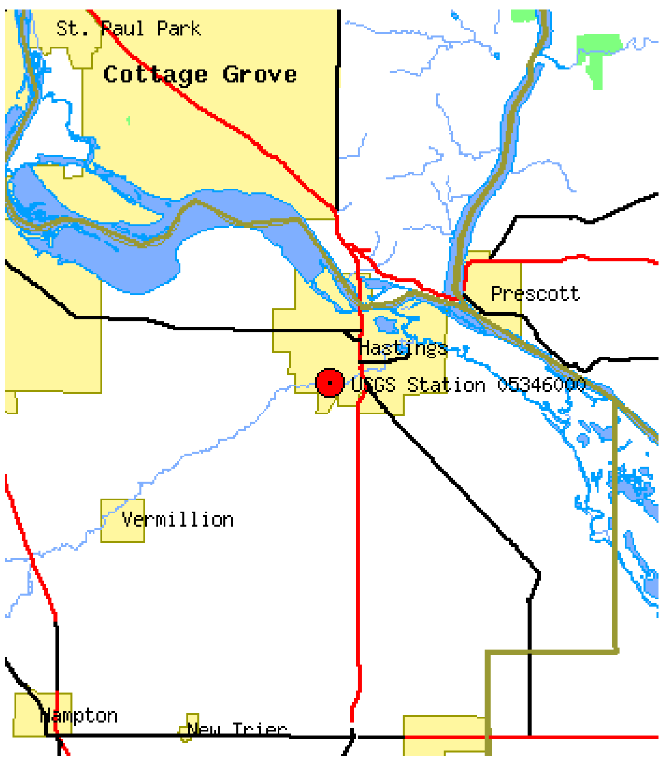


Figure 4-2. Site station map for USGS gage 05346000.

Figure 4-3. MCES gaging station on the Vermillion River at ConAgra Mill, Hastings.

Records at the two USGS gages overlap for two brief periods: May 1, 1942, through July 7, 1945, and October 1, 1989, through October 2, 1990. Figure 4-4 and Figure 4-5 show the flows at each gage during these two periods. USGS gage 05345000 overlaps with the MCES gage for 1994–2002; results are shown in Figure 4-6.

Table 4-1. Station Information and Periods of Record for Flow Gages on the Vermillion River

Parameter	USGS Gage 05345000	USGS Gage 05346000	MCES Gage 213567
Latitude	44°40'00"	44°43'12"	
Longitude	93°03'17"	92°51'57"	
Drainage area (mi^2)	129	195	277.98
Gage datum (ft MSL)	851.99	Not listed	Not listed
Period of record	4/12/1942–7/7/1945 10/1/1973–9/30/2002	5/1/1942–9/30/1947 10/1/1989–10/2/1990	1/1/1994–12/31/2002
Minimum flow	8.4	6	31.7
Maximum flow	3,000	1,340	2,035
Average flow	70	78.8	151.9

Note: As of 2/19/04, flows for the MCES gage at Hastings are available through the end of 2003; however, they were not supplied in time to be included in this report.

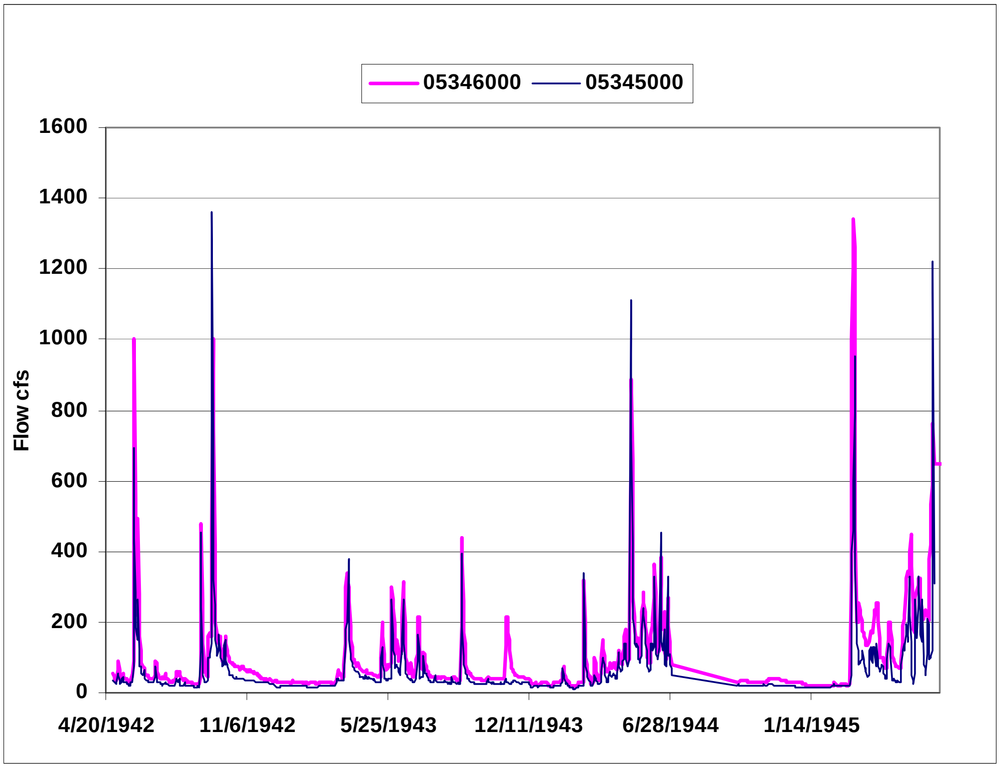


Figure 4-4. Flow data at USGS gages 05345000 and 05346000 from May 1, 1992,through July 7, 1945.

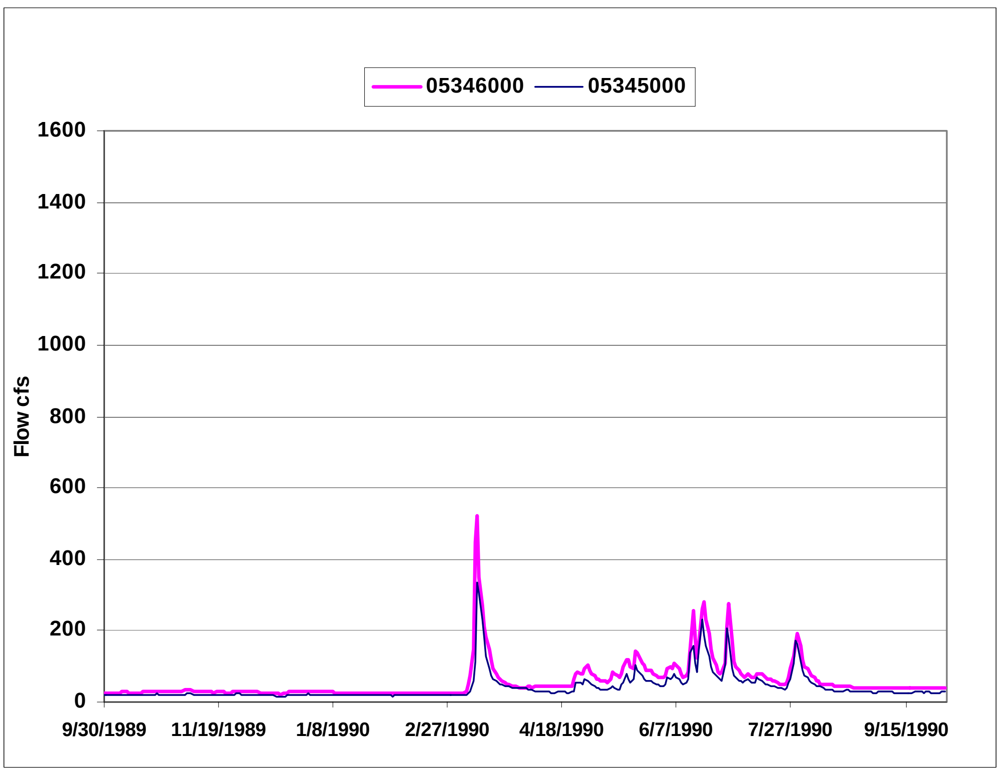


Figure 4-5. Flow data at USGS gages 05345000 and 05346000 from October 1, 1989,through October 2, 1990.

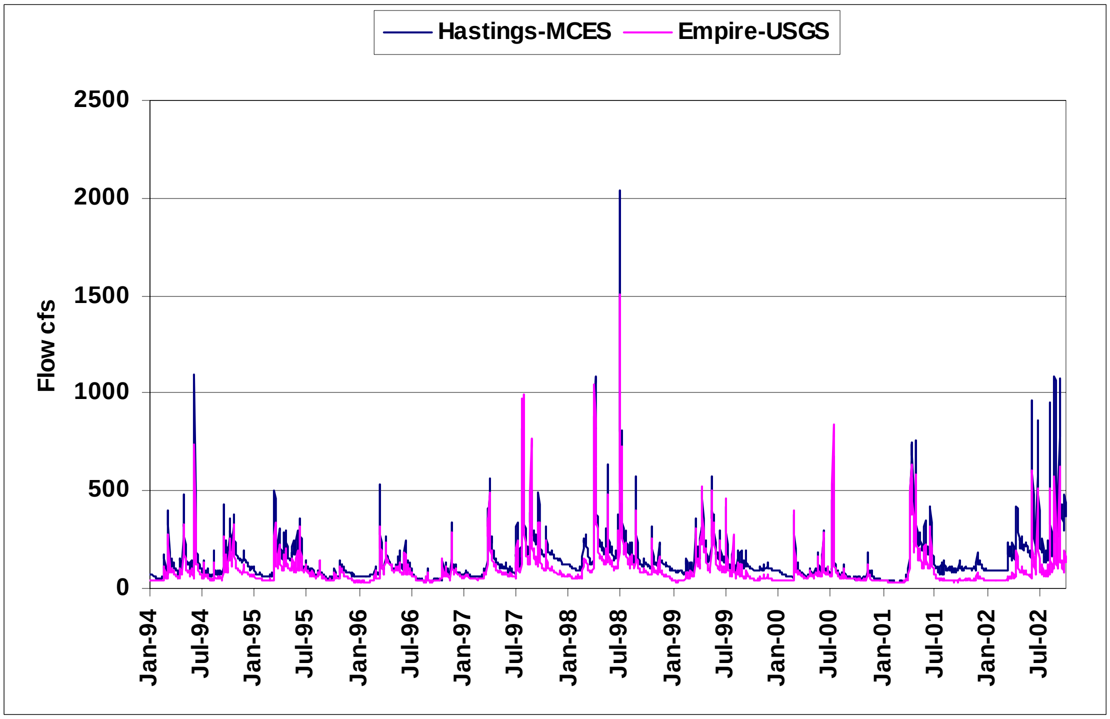


Figure 4-6. Flow data at USGS gage 054345000 and MCES Hastings gage for 1994–2002

The Typical lag time for flow peaks appears to be approximately 1 day from Empire to Hastings.

4.1.1.2 Predicting Missing Flows at Hastings

The ConAgra Mill and dam in Hastings are a few miles upstream of the Mississippi River floodplain that forms the boundary between the Upper and Lower Vermillion River systems. Flow at this point will be essential to drive any hydraulic/hydrologic analyses of the Lower Vermillion. From 1994 on, gaged data reported by MCES can be used directly to establish this boundary. Prior to 1994 flows at the ConAgra dam must be estimated.

4.1.1.2.1 Multiple Regression on Actual Flow and Lagged Flow Observed at Gage 05345000

A multivariate regression on observed flows and 1-day lagged flows at gage 05345000 was used to predict flows at both USGS gage 05346000 and the MCES Hastings gage. Only 1995–2002 results are used for the MCES regression because most of the 1994 data are estimated. Regression statistics are summarized in Table 4-2.

Table 4-2. Multivariate Regression Predicting Flow at Hastings from Observed and Lagged Flows at Gage 05345000 (Empire)

Statistic	Flow at USGS Gage 054346000	Flow at MCES Hastings Gage
Adjusted R^2	0.7677	0.8479
Standard error	56.00	50.72
Observations	1438	2829
Intercept	17.30	26.08
Coefficient on same day flow	0.6165	0.6046
Coefficient on lag-1 flow	0.5595	0.6547

Observed and predicted flows at the ConAgra Mill in Hastings are compared in Figure 4-7. The fit appears quite strong, with an R^2 of 0.93.

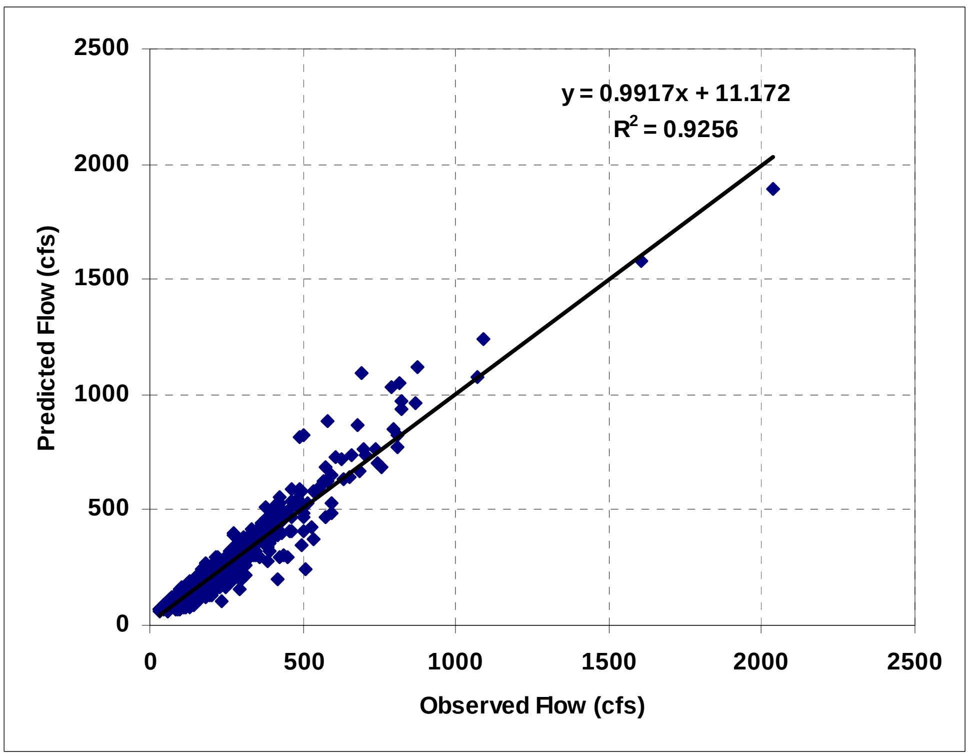


Figure 4-7. Comparison of observed and predicted flows at the MCES gage at Hastings 1995—2002.

4.1.1.2.2 Comparison of Flows at USGS and MCES Hastings Gages

USGS and MCES flow measurements at Hastings do not overlap in time. However, both stations may be related to the upstream gage at Empire. Regressing observed flows at the MCES gage on flows predicted at USGS gage 05346000 yields the relationship

$$MCES = 3.162 + 1.538 \cdot gage\ 05346000,$$

with an R^2 of 79.3 percent. The coefficient is somewhat less than the ratio of reported drainage areas (1.68), likely reflecting the fact that impervious cover is concentrated in the headwaters of the watershed. This relationship can be used as an alternative to predict flows at the MCES gage site for the brief period from October 1, 1989, to October 2, 1990, when the USGS gage at Hastings was active.

4.1.2 Flow Between Mississippi River Pool 3 and the LVR

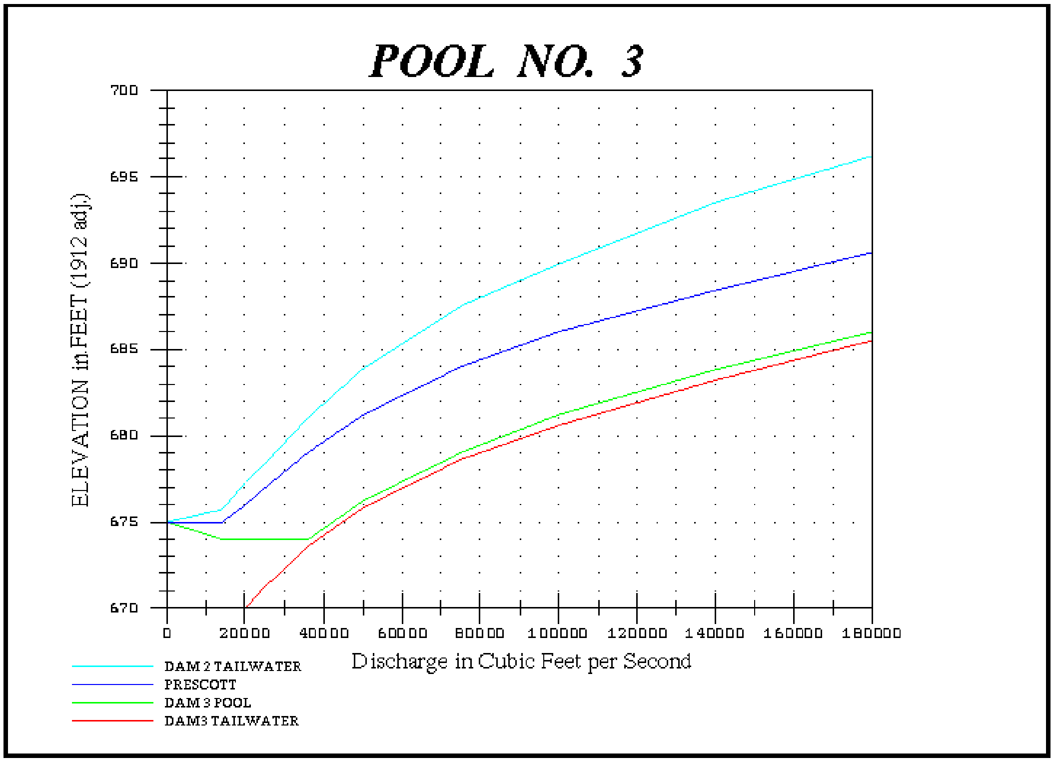
Interflow between Mississippi Pool 3 and the LVR is a dominant feature of the system. This section summarizes the available data on these interflows and their controlling factors.

4.1.2.1 Operation of Mississippi Lock and Dam 3

Mississippi River Lock and Dam 3 was built in 1937-1938 and became operational in 1938 (Figure 4-8). The dam is operated by the St. Paul District, USACE, for the primary purpose of maintaining a navigational channel 9 feet deep.

Figure 4-8. Mississippi River Lock and Dam 3 (November 20, 2003).

The primary control point for Pool 3 is the gage at Prescott, Wisconsin. The pool is operated to maintain a target elevation of 675 feet (NGVD 1912) at the Prescott gage (Figure 4-9), with a target tailwater elevation of 667 Dennis Erickson, USACE St. Paul, personal communication to Kim Gorman, Tetra Tech, Inc. February 20, 2004). During lower flows, there is a drop in water surface elevation of about 5 feet across Lock and Dam 3. At higher flows above (about 375 cfs), the gates are opened, establishing a near-level surface across Lock and Dam 3.



http://www.mvp-wc.usace.army.mil/projects/Lock3.shtml, accessed March 18, 2004.

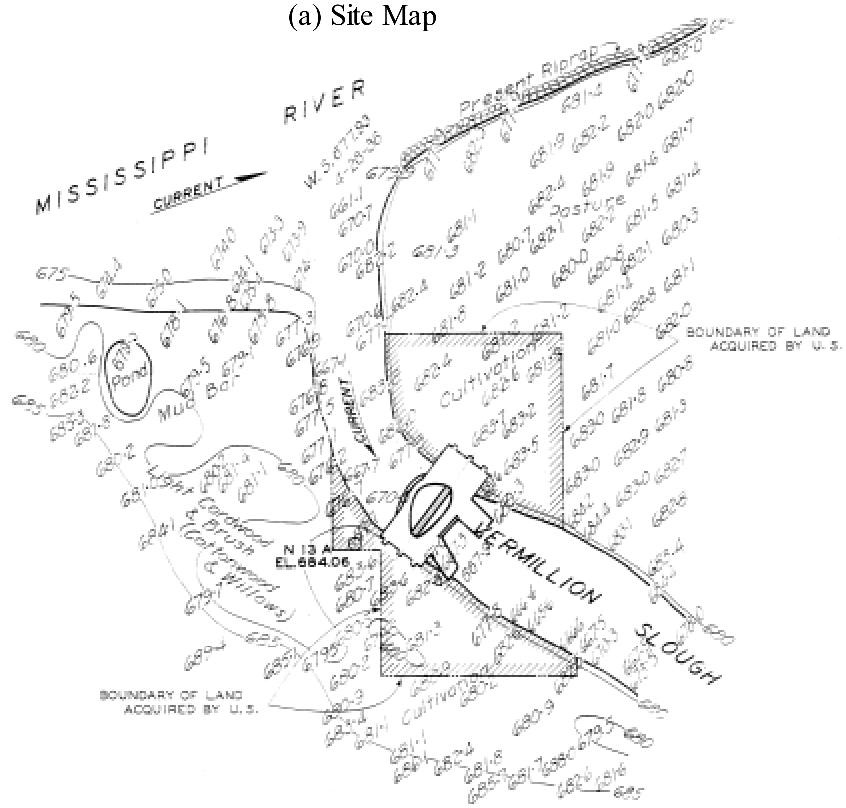
Figure 4-9. Operating curve for Mississippi Lock 7 Dam 3

4.1.2.2 Vermillion Slough

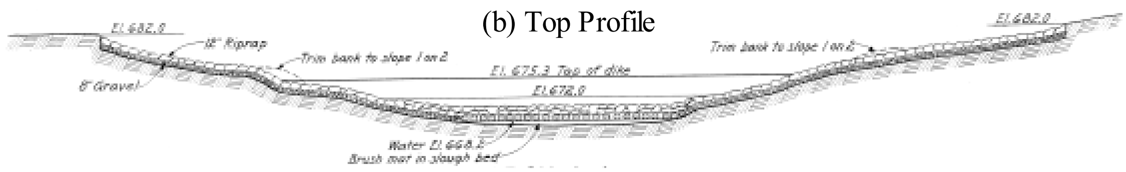
Vermillion Slough, southeast of Hasting, is the first major connection of the Mississippi River and the LVR. The channel is about 1.8 miles long and meanders significantly. According to the Dakota County Flood Insurance Study (FIS) (Bohlen Surveying, 2002), the channel longitudinal profile is very flat and nearly horizontal, with an average bottom elevation of about 670 (NGVD 1929). The channel is controlled by a rock-fill dike near its entrance (River Mile 813.2) on the Mississippi River, which is maintained by the USACE. The dike top elevation is 675.3 feet (NGVD 1912). 0 shows the dike site, profile, and cross section. Water can flow through the slough in either direction depending on the relative stages of the LVR and the Mississippi River. As discussed below in Section 4.1.2.5, flows from the Mississippi River into the LVR via Vermillion Slough might occur on more than 60 percent of days during the summer.

Sufficient information to conduct a detailed analysis of flow across the Vermillion Dike is not yet available. However, a stage-discharge relationship for flow in both directions over the dike can be developed using a weir equation. The equation requires only the stage on both sides of the dike and the dike geometry. The dimensions of the trapezoidal shape of the dike were approximated using 2-foot interval topographic data. The stage-discharge relationship shown in Figure 4-11 was developed for modular flow from the Mississippi into Vermillion Slough. If the flow becomes submerged due to high tailwater elevations in the slough, a reduction factor can be applied to the calculated discharge. A similar relationship can be developed for flow into the Mississippi from Vermillion Slough. As Figure 4-11 shows, the stage-discharge relationship is not valid for stages above 682 feet because the slough banks are overtopped at approximately this elevation.

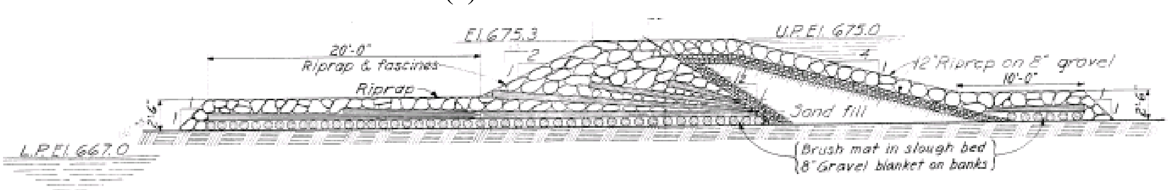
(a) Site Map



(b) Top Profile



(c) Dike Cross Section



Source: USACE, 1936. Vertical datum does not show on the drawing; 1912 NGVD assumed.

Figure 4-10. Vermillion Slough dike.

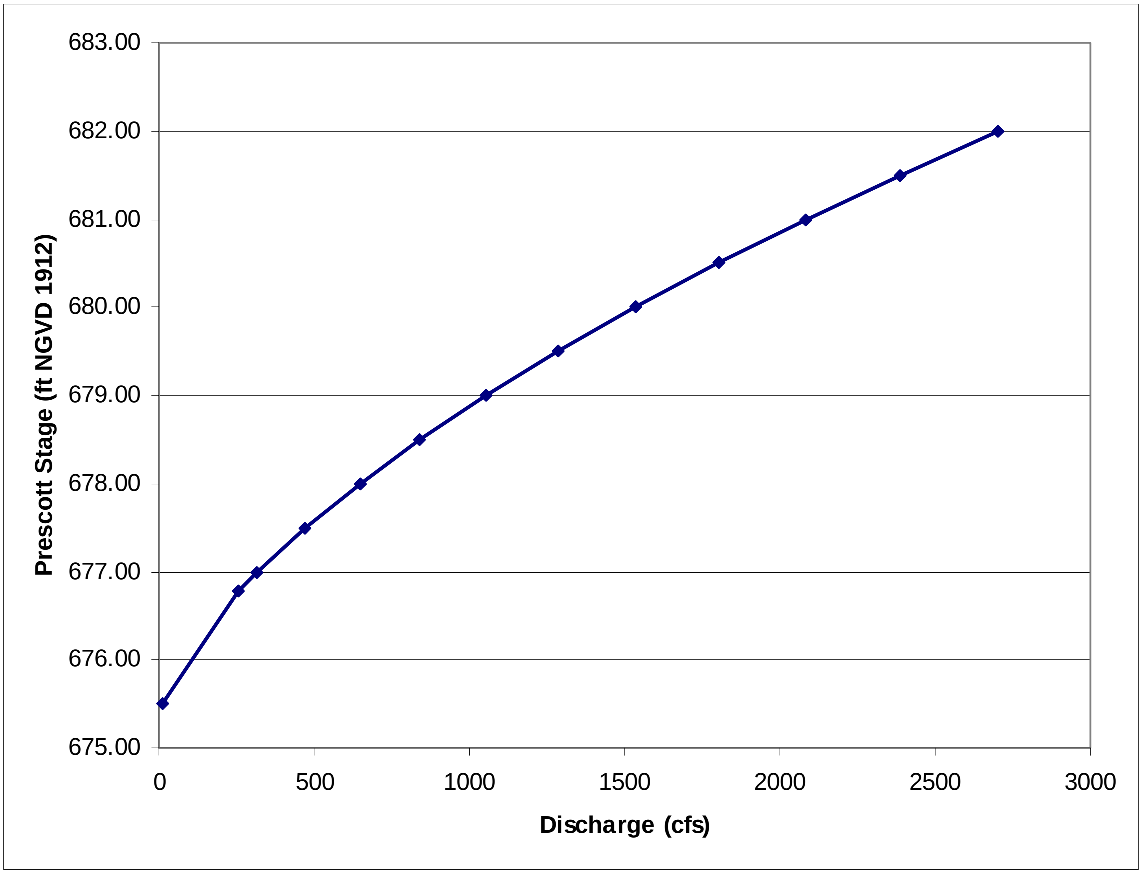


Figure 4-11. Preliminary stage-discharge relationship for the Vermillion Slough (modular flow into the slough).

It should be noted that the preliminary discharge estimates shown in Figure 4-11 assume that water surface elevation within the Vermillion Slough is free to fall below 675.5 feet. The remains of the abandoned, deteriorating control structure at the Three Bridge site on the LVR downstream of the Vermillion Slough confluence might limit flows into the LVR and maintain a minimum stage in Vermillion Slough (UMRSEMP, 1990). This structure seems to have been originally installed to direct Upper Vermillion River flows through Vermillion Slough (its natural channel prior to the impoundment of Pool 3), but it was abandoned and has apparently eroded significantly. No survey information (either as-built or current) for this dike is available. Natural grade control in Vermillion Slough, along with the influence of the Three Bridge Dike, will need to be better evaluated to develop representative rating curves for flows into and out of Vermillion Slough.

4.1.2.3 Truedale Slough and Culvert

Truedale Slough is one of three major connection channels between the LVR and the Mississippi River (Figure 4-12). It is one-half mile north of Mud Hen Lake and Carter Slough. The slough entrance is near Mississippi River Mile 808.5.

Figure 4-12. Lower Vermillion River at DNR Public access below Truedale Slough (November 20, 2003).

A rockfill closure dike and a 48-inch culvert control the inflow from Mississippi River Pool 3 to Truedale Slough. The site plan is shown in Figure 4-13. The culvert is upstream of Truedale Slough dike, running north-south from the Mississippi River to a backwater area of the Vermillion River. The culvert might have been installed by MNDNR (USACE, 1987). Accurate culvert invert elevations cannot be identified from the information provided by USACE to date.

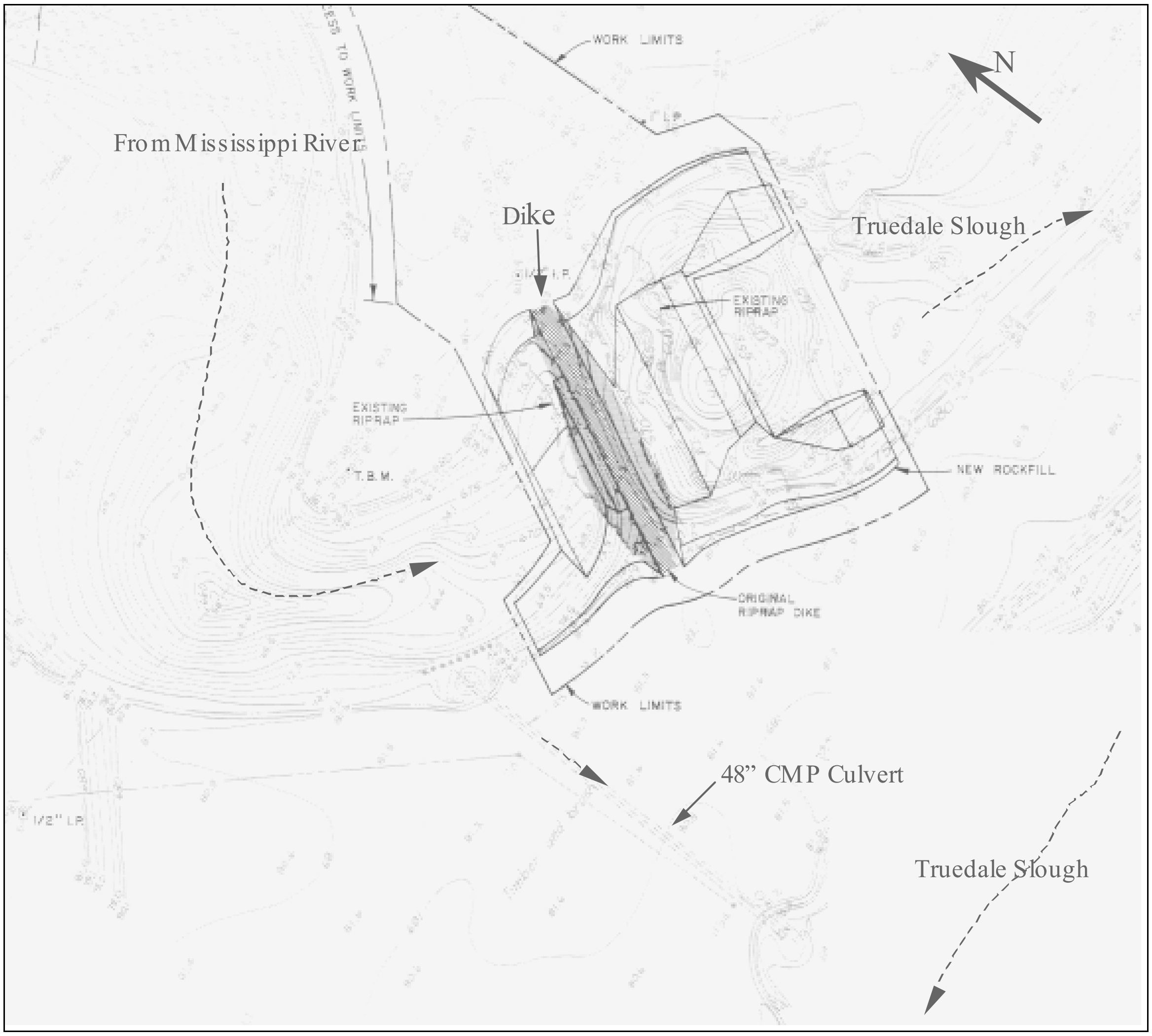


Figure 4-13. Plan View of Truedale Slough Dike and Culvert

The USACE rebuilt the Truedale Slough Dike in 1986 as part of the ongoing project to maintain the integrity of Pool 3 (USACE, 1987) and keep it from bypassing Pool 3 via the LVR. The top profile of the dike is displayed by cross-section at station 0+00 on the USACE's 1987 drawing (M-L3-52/42, Sheet 7 of 11), as plotted here in Figure 4-14. It shows that the dike top is not at constant elevation, with the spot elevation ranging from 676.58 (NGVD 1912) and 677.21 (NGVD 1912). The top of the overbank is about 682 (NGVD 1912). This means that the dike is overtopped at 676.58 (NGVD 1912), instead of 677.5 (NGVD 1912) as cited in several MNDNR documents.

The Federal Highway Administration (FHWA) culvert design program HY8 (embedded in HYDRAIN) was used to assess the discharge through the culvert and the dike overflow from the Mississippi River at various relative stages. HY8 automates the design methods described in "Hydraulic Design of Highway Culverts" (FHWA, 1985); "Hydraulic Design of Energy Dissipators for Culverts and Channels" (FHWA, 1983); and "Hydrology" (FHWA, 1984). The inputs include culvert shape and type, invert elevations, inlet type, site data, selected minimum, design, and maximum discharges, embankment/dike profile, and tailwater. For a given culvert setting, the program calculates the culvert inlet headwater elevations for the selected discharges, from which the discharge and stage relationship can be defined. HY8 also calculates the culvert flow and overflow on the dike.

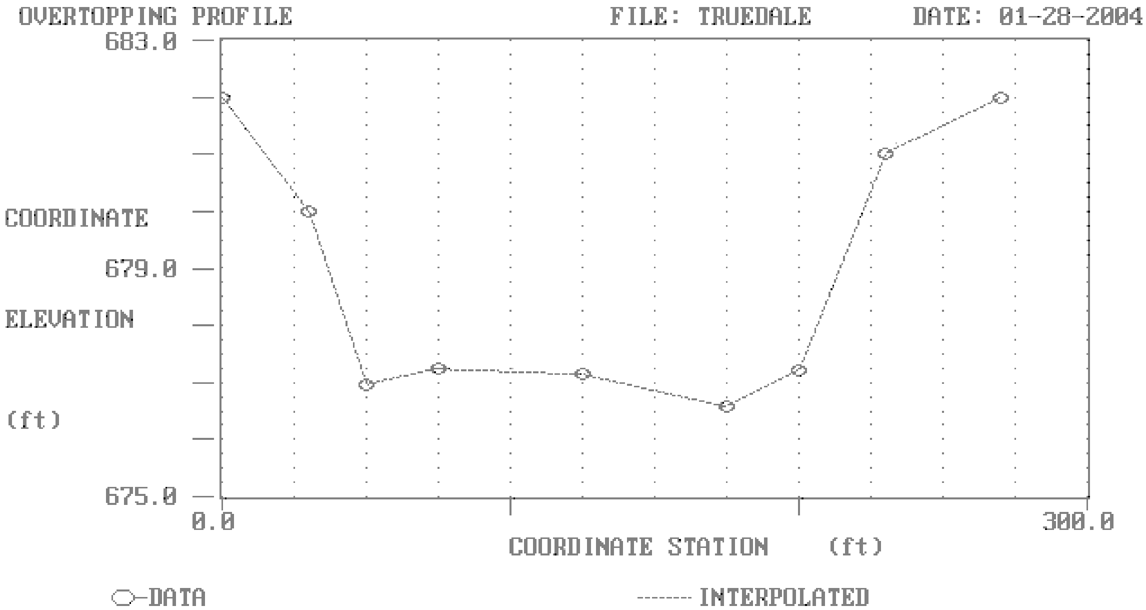


Figure 4-14. Truedale Dike Top Profile (USACE, 1986)

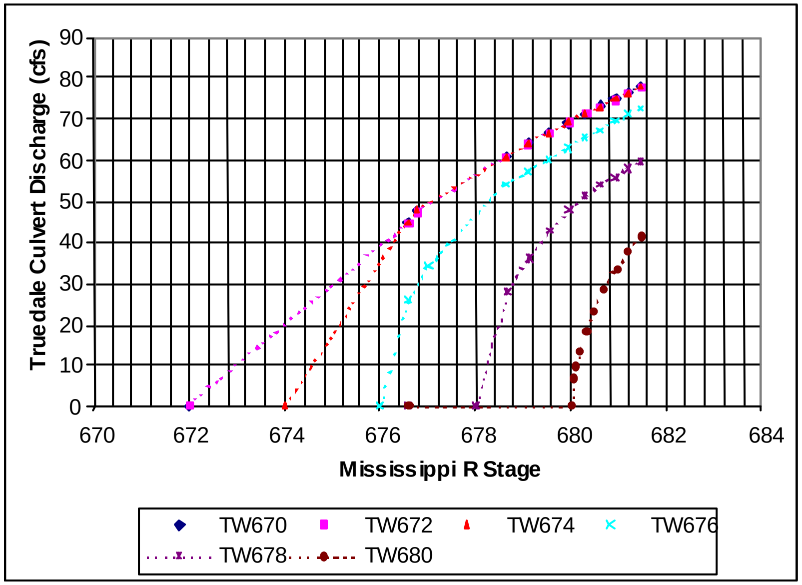
Because the exact culvert invert elevations are not known, three invert elevations —670 feet, 671 feet, and 672 feet— (NGVD 1912) were used to assess the discharge sensitivity to the culvert setting, assuming the culvert is near horizontal. Based on review of the site plan, it is believed that the culvert inlet is in the range of these elevations. The various scenarios of different culvert invert elevations and Truedale Slough tailwater elevations were evaluated through multiple runs of HY8. The output is summarized in the Appendix.

Appendix A shows the relationship of Mississippi River stage near the Truedale Slough entrance and culvert/dike overtop discharges for certain assumed culvert invert elevations and tailwater elevations. Figure 4-15 shows the culvert rating curves with respect to invert elevations 670, 671, and 672 (NGVD 1912). It should be noted that the Mississippi River stage near the slough entrance is rarely lower than 674 feet (NGVD 1912). The culvert delivers flows to the LVR most of the time throughout the year. The rating curves are extended to zero discharge stages only for comparison.

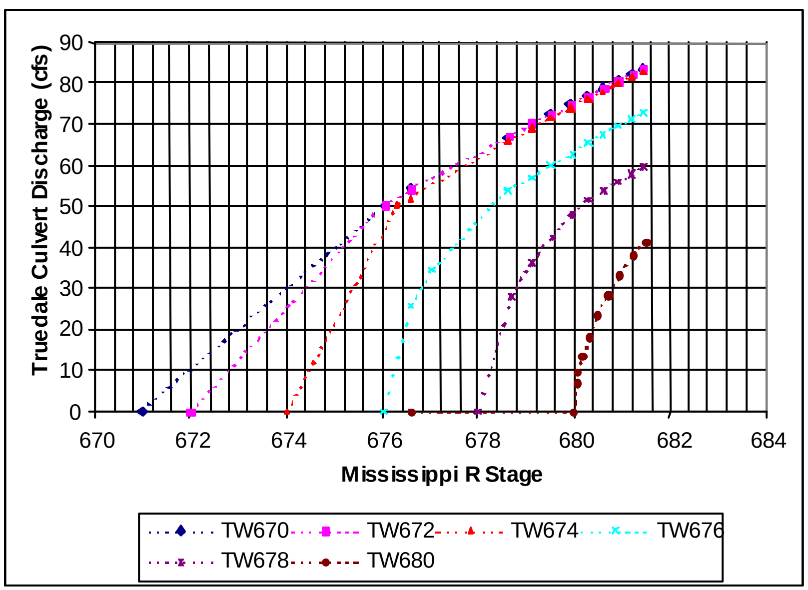
These figures show that when the stage in Truedale Slough is low and the culvert is not submerged and is in inlet control, the culvert invert elevation influences discharge significantly. An actual survey of the culvert is needed to refine estimates for these conditions. When the Truedale Slough stage is high enough to submerge the culvert and the culvert is in outlet control, the culvert elevation does not affect discharge. The discharge is controlled by the head fall from the Mississippi River to the slough. 0 shows a comparison of discharges under three invert elevations in the same plot. When the tailwater is low, a 1-foot increase on culvert invert elevations results in up to a 10-cfs flow decrease, depending on the Mississippi River stage. The Appendix shows the dike overtop discharge at various backwater conditions.

After the culvert invert elevation is verified through survey, the proper rating curves can be used to interpolate the slough flow series based on the slough backwater stage and the Mississippi Pool 3 stage. However, the rating curves by HY8 are applicable only when Mississippi River stages are not higher than the Truedale Slough overbank top (around 682 feet) and the Mississippi flood does not inundate the slough area.

(a) Culvert Invert at 672 (NGVD 1912)



(b) Culvert invert at 671 (NGVD 1912



(c) Culvert Invert at 670 (NGVD 1912)

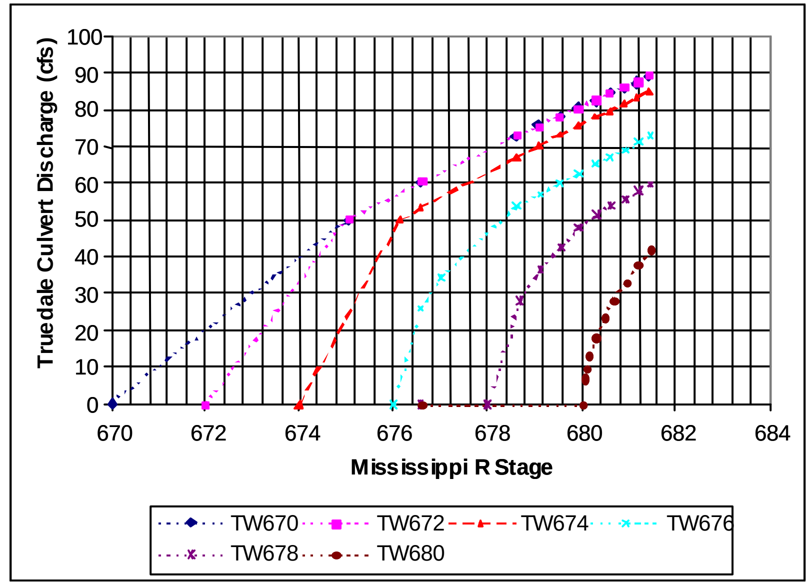


Figure 4-15. Truedale Slough culvert discharge as a function of Mississippi River Pool 3 stage.

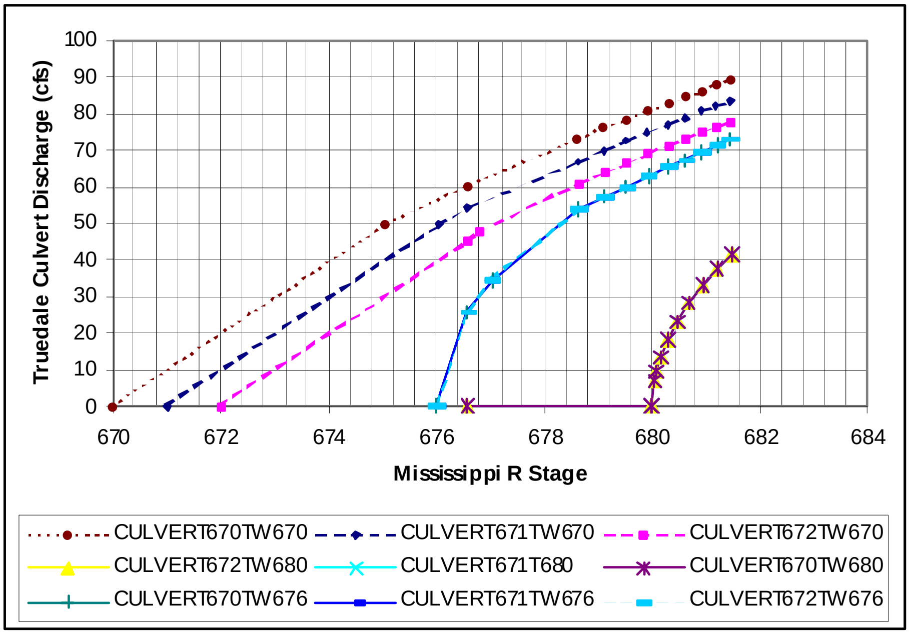


Figure 4-16. Truedale Slough culvert discharge sensitivity to invert elevation.

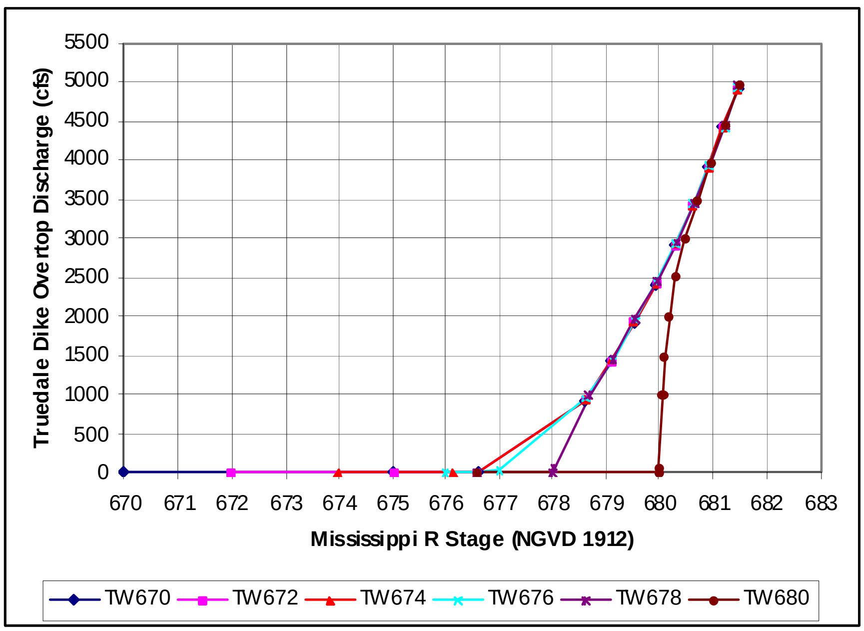
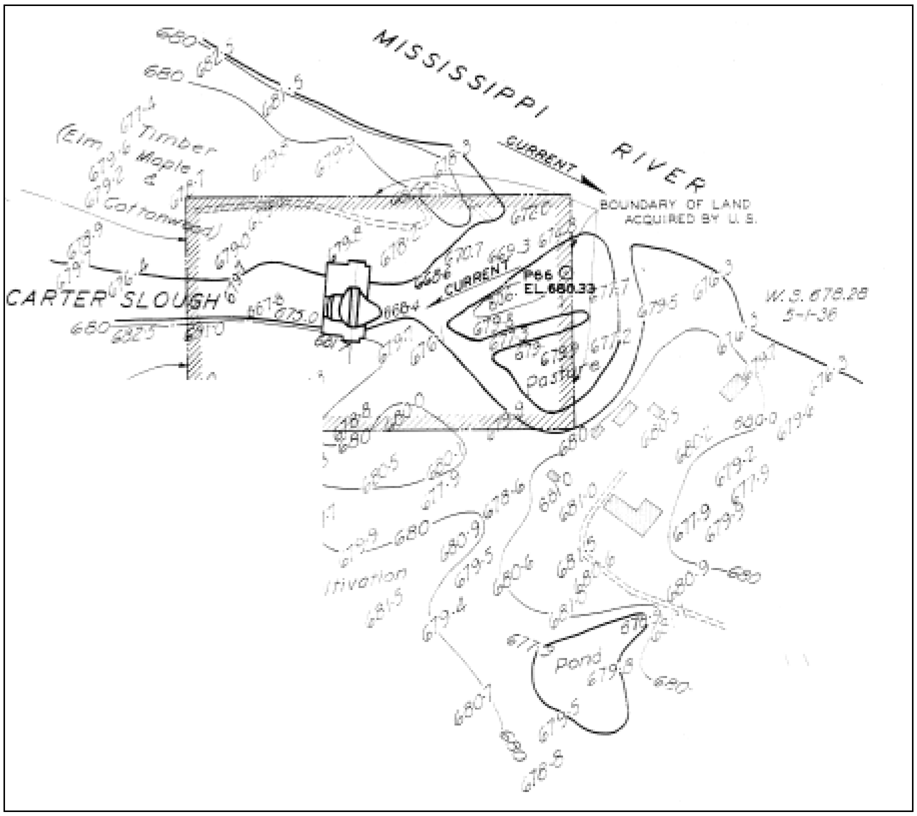


Figure 4-17. Truedale Slough dike overtop discharge at various tailwater elevations.

4.1.2.4 Carter Slough/Mudhen Lake

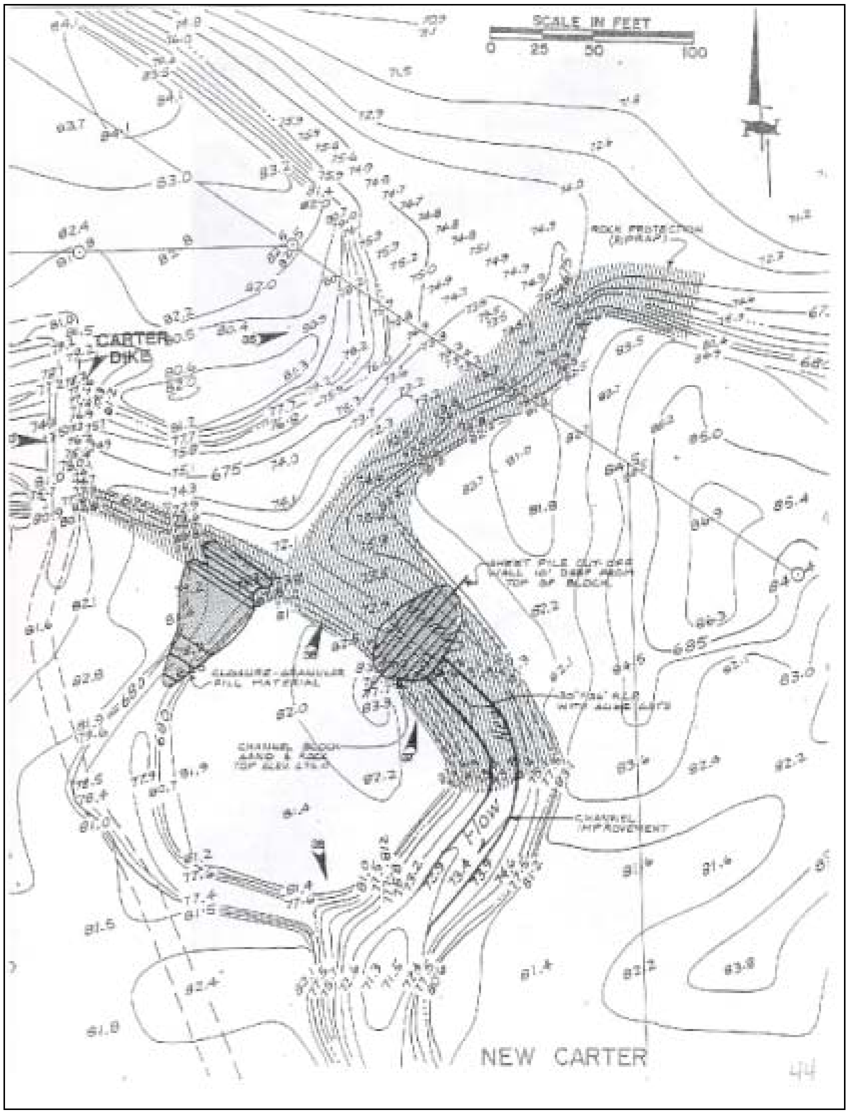
Carter Slough, 1 mile south of Truedale Slough, is the third major connection between the LVR and the Mississippi River.. It connects to Mud Hen Lake and then Round Lake before entering the LVR. The flow through the slough is controlled by the dike at the entrance to the Mississippi River (River Mile 807.3) and another dike (DNR dike) near the confluence with the LVR. Thus far, no site information has been identified for the DNR dike.

The USACE constructed the original Carter Slough in 1936 to prevent Mississippi Pool 3 from draining to Mud Hen Lake. Figure 4-18 shows the site map. The top elevation, initially 675.3 feet (NGVD 1912), was raised to 677.5 feet in 1967 (ref. USACE drawing). Investigations by the USACE in 1987 revealed that the dike was being bypassed in two locations to the southwest, forming a more direct channel to Mud Hen Lake and, via Round Lake, to the LVR. Figure 4-19 shows the site map in 1987, including the old dike and proposed locations for two new dikes to control the new channel. Those dikes were never constructed. Instead, according to the USACE (M34 T CC/FNO.0.1, Plate 21), a new dike was constructed at the Carter Slough entrance in summer 2002. The new dike top elevation is 679.0 feet (NGVD 1912), as shown in Figure 4-20. Figure 4-21 is a 2003 infrared aerial photo showing the Carter Slough and Mud Hen Lake.



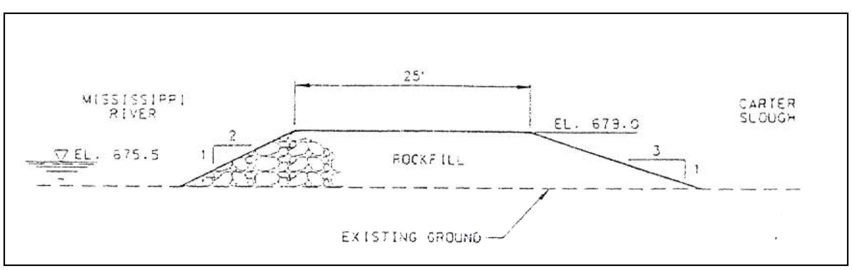
Source: USACE, 1936. Vertical datum does not show on the drawing; 1912 NGVD assumed.

Figure 4-18. Carter Slough dike plan in 1936.



Source: USACE, 1987

Figure 4-19. Carter Slough entrance site plan in 1987.



Source: USACE, 2002.

Figure 4-20. Carter Slough new 2002 dike section.

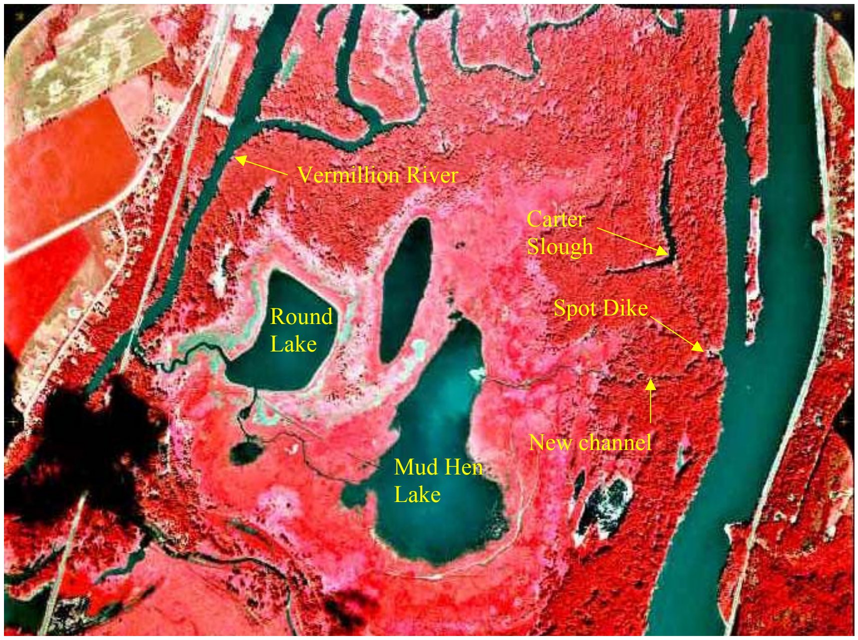


Figure 4-21. Carter Slough and Mud Hen Lake aerial photo

4.1.2.5 Frequency of Mississippi River Intrusions into the LVR

The frequency with which flows from the Mississippi intrude into the Lower Vermillion is largely controlled by the stage in Pool 3. When this stage overtops the dikes, Mississippi River water enters the LVR, except during those conditions when high flows in the Upper Vermillion produce an even higher stage in the LVR.

The relevant dike elevations controlling flow between the two systems are (as documented in previous sections) 675.3 feet (1912 NGVD) for Vermillion Slough, 676.58 feet for Truedale Slough, 677.5 feet for Carter Slough (prior to reconstruction in 2000), and 679.0 feet for Carter Slough (after reconstruction in 2000).

Mississippi Pool 3 is gaged within the neighborhood of these sloughs at Prescott, Wisconsin (River Mile 811.4). The entrance to Vermillion Slough is at about River Mile 813.1, Truedale at River Mile 808.5, and Carter at River Mile 807.3 (approximate values). Based on linear interpolation of the flow profile at stage around 675 feet between Lock and Dam 2 tailwater, Prescott, and Lock and Dam 3 forebay, stage at Vermillion Slough should be about equal to stage at Prescott, while stage at Truedale Slough and Carter Slough should be about 0.2 and 0.3 foot lower, respectively. Thus frequency of overtopping into Vermillion Slough can be evaluated at Prescott stage of 675.3 feet (no correction), while overtopping at Truedale and Carter Sloughs should correspond to approximate Prescott stages of 676.78 and 677.8/679.3 feet. Prescott stage records are available from January 1, 1940, through December 17, 2003 (with a 2-month gap in the winter of 1994). The records are shown in Figure 4-22 and range from 671.7 to 693.1 feet. Frequency analysis of the daily stage (Table 4-3) shows that, on an annual basis, flow from the Mississippi should enter Vermillion Slough about 50 percent of the time and enter Truedale and Carter Sloughs about 20-25 percent of the time. Following the reconstruction at Carter Slough, flow through this channel was reduced to about 13 percent of the time. If the analysis is conducted for only the summer months, the frequency is even higher, with flows entering Vermillion Slough about 60 percent of the time and entering Truedale Slough around 37 percent of the time.

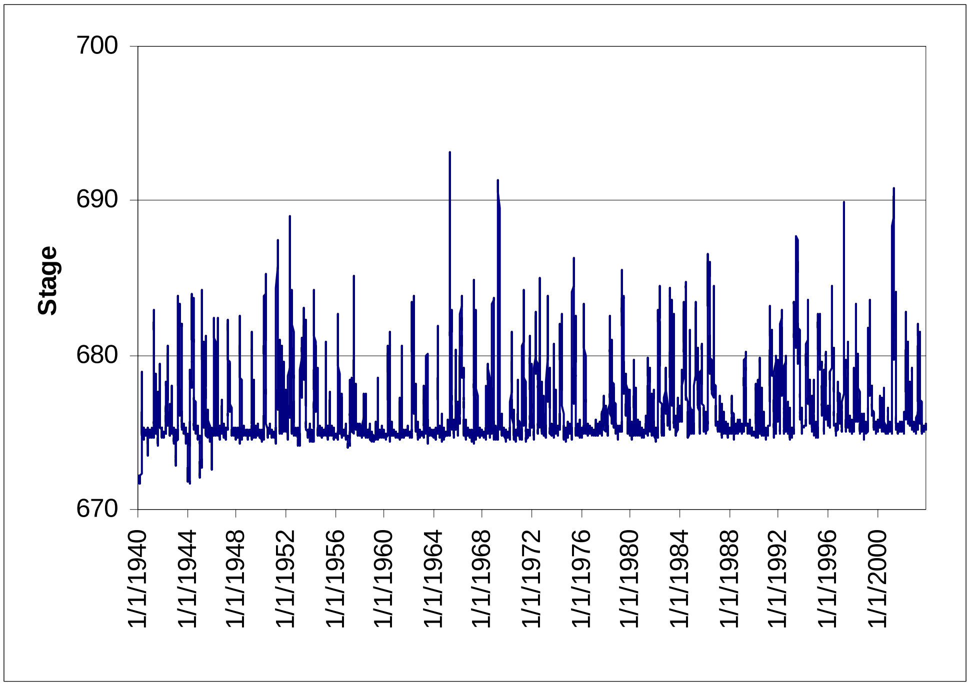


Figure 4-22. Stage recorded in Mississippi Pool 3 at Prescott (NGVD 1912).

Table 4-3. Frequency of Pool 3 Elevations Sufficient to Enter Lower Vermillion System (NGVD 1912)

	Prescott	Total	May-Sept	June-Aug
	Critical Stage	Percent Greater	Percent Greater	Percent Greater
Vermillion Slough	675.3	49.85	60.39	60.10
Truedale Slough	676.78	25.71	36.96	35.88
Carter Slough (prior to 2002)	677.8	19.56	27.33	25.59
Carter Slough (after 2002)	679.3	12.71	16.50	14.09

A histogram of the full series of recorded stages at Prescott is shown in Figure 4-23. Fully 20 percent of the recorded stages are greater than 680 feet providing heads of about 4.7 feet at Vermillion Slough and 3.2 feet at Truedale Slough; 10 percent of the stages are greater than 685 providing heads of 9.7 and 8.2, feet respectively. Thus, there is clearly frequent opportunity for large flows to enter the LVR.

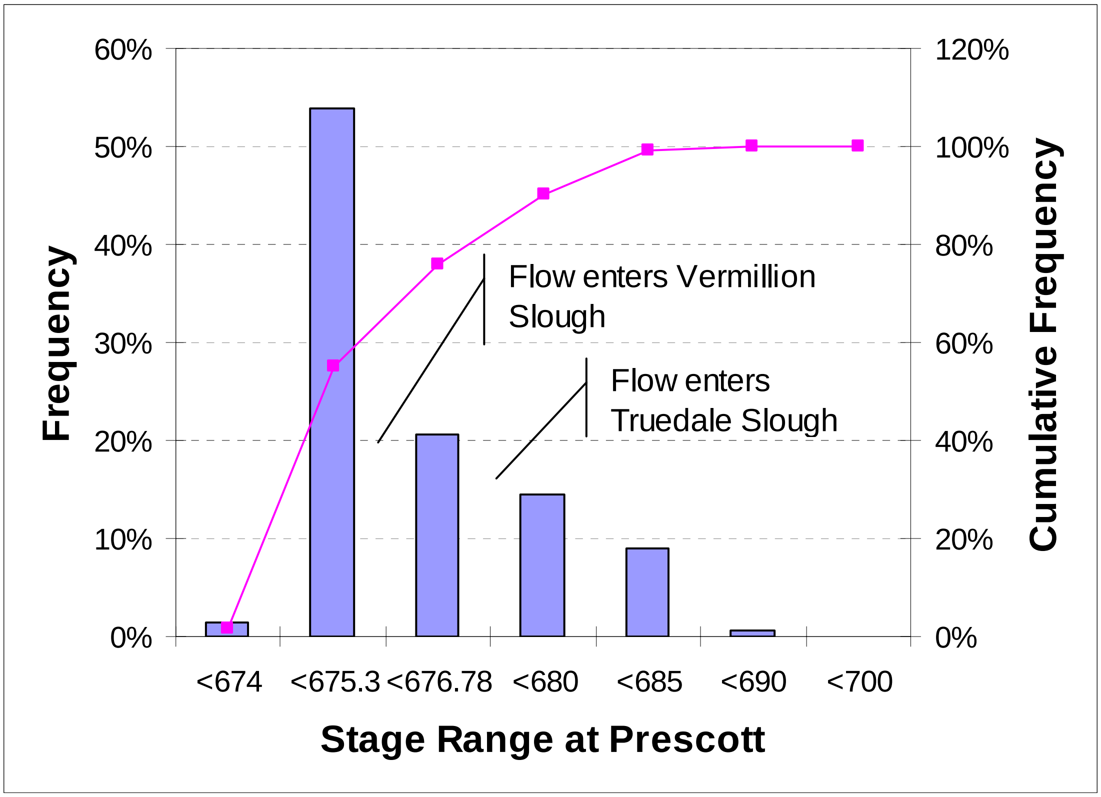


Figure 4-23. Histogram of Pool 3 stage at Prescott, 1940-2003 (NGVD 1912).

4.1.3 Groundwater Flow in the LVR

Estimates of groundwater flow between the Vermillion and Mississippi rivers are primarily based on studies conducted at the Prairie Island Indian Reservation, which exists as an island among the lake system of the LVR. Two reports discuss the direction of groundwater flow during various flow regimes.

The USGS investigated hydrology and water quality at the Prairie Island Indian Reservation and collected samples collected from 1994 to 1997 (Cowdery, 1999). At that time 106 groundwater wells had been installed by various agencies, and these wells were used to measure groundwater head at several locations on the reservation.

The surficial aquifer below the Reservation is composed mostly of sand and gravel with a thickness of 130-200 feet. Under normal flow conditions, groundwater flows through the aquifer from the direction of the Mississippi River toward the Vermillion River because Lock and Dam 3 maintains stage in the Mississippi River approximately 6 feet higher than normal stage in the Vermillion River.

The aquifer below Prairie Island is also recharged vertically through the land surface by snowmelt, rainfall, and floodwaters. During spring runoff and periods of high rainfall, the Mississippi and Vermillion rivers are near the same stage, so minimal groundwater flows across the aquifer from one river to the other. Instead, the groundwater table below the Island rises above the surrounding water table. As a result, groundwater flows out radially, with the highest flows toward the largest energy gradient. Following heavy rains in July 1997, USGS estimated flows from the aquifer to surrounding water tables, wells, and surface waters to be 700,000 ft^3/d (234,000 ft^3/d was discharged to Prairie Island wells). A water-table surface graph in the report shows a 1-foot gradient from the Prairie Island groundwater table to the surrounding water tables.

In a memo from Scot Johnson to Mike Davis dated January 4, 1996, Mr. Johnson described the hydrology of the LVR during low-flow conditions. He reported that during baseflow conditions, the groundwater recharge from the Mississippi River to the Vermillion River is about 70 ft^3/s (6 million ft^3/d) based on measurements at Clear Lake and Rattling Springs Lake during October 1990. Stages at the Mississippi and Vermillion rivers were not reported.

As both Clear Lake and Rattling Springs Lake are fed primarily by groundwater, observed water quality in these lakes provides some indication of loads to the LVR via groundwater.

4.1.4 Local Tributaries to the LVR

To estimate flow volumes and water quality impacts from the smaller tributaries of the LVR, subwatersheds for the Upper Mississippi hydrography coverage were manually delineated in ArcView by referencing the USGS topographic maps. Two perennial streams that were not included in the Upper Mississippi hydrography coverage but were shown on the USGS topographic maps were also delineated. Most of the resulting subwatersheds are referenced by river mile along the Vermillion River. River Mile 0.00 was set at the confluence of the Vermillion and Mississippi rivers. Approximate river miles were assigned in half-mile increments using ArcView's measure tool. The resulting delineations and river miles are shown in Figure 4-24, on which watersheds 1-17 represent the direct drainage to the LVR downstream of the MCES flow gage at Hastings.

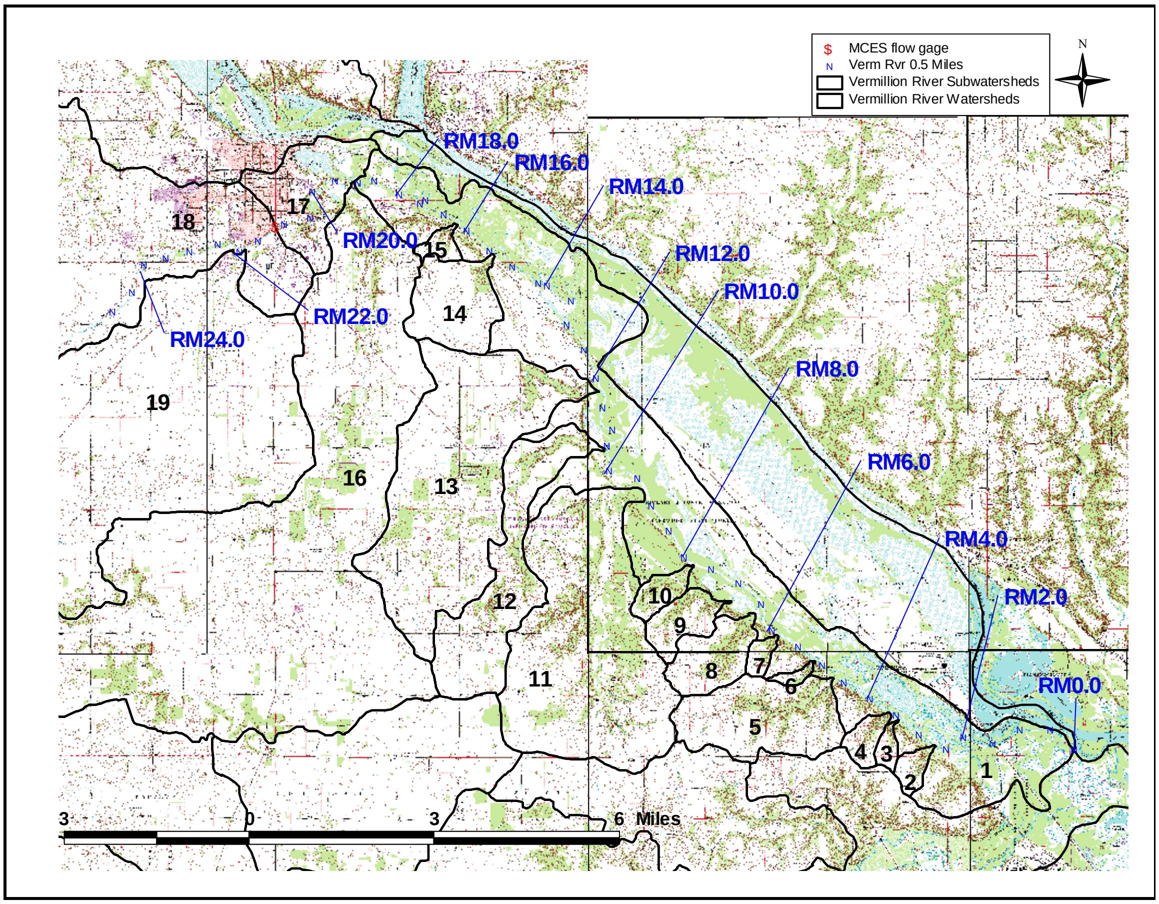


Figure 4-24. River miles and subwatersheds in the Lower Vermillion drainage area.

There are no existing flow gages along the LVR or its tributaries, flows must be estimated. MCES has measured flow along the Upper Vermillion River at 2005 Vermillion Street in Hastings as discussed previously. Initial estimates of flow from the other tributaries can be calculated by multiplying the gaged flow by the ratio of each tributary's drainage area to the gaged drainage area. Drainage areas and ratios for each subwatershed are summarized in Table 4-4. Subwatershed 18 represents the drainage area above the MCES gage, so its ratio is shown as 1.0000. Table 4-5 summarizes the estimated mean flow from the major regions in the watershed over the period of available MCES gaging at Hastings (1994-2002). For this period, direct tributaries to the LVR are estimated to add about 28 percent to the flow contributed by the Upper Vermillion River.

Table 4-4. Ratios of Drainage Areas for the Subwatersheds in the Lower Vermillion Watershed

ID	Description	Area (mi^2)	Ratio of Drainage Area to Gaged Drainage Area
1	Floodplain of the LVR	18.6073	0.0669
2	Enters the Vermillion River at River Mile 2.68	0.3006	0.0011
3	Enters the Vermillion River at River Mile 3.42	0.2092	0.0008
4	Enters the Vermillion River at River Mile 3.58	0.3978	0.0014
5	Enters the Vermillion River at River Mile 4.70	2.9297	0.0105
6	Enters the Vermillion River at River Mile 5.13	0.1279	0.0005
7	Enters the Vermillion River at River Mile 5.90	0.2274	0.0008
8	Enters Rattling Springs Below Lower Lake	1.2700	0.0046
9	Enters Lower Rattling Springs Lake	0.8301	0.0030
10	Enters the Vermillion River at River Mile 7.79	0.4555	0.0016
11	Etter Creek; enters the Vermillion River at River Mile 9.23	9.1778	0.0330
12	Enters the Vermillion River at River Mile 10.44	3.8694	0.0139
13	Enters the Vermillion River at River Mile 11.77	8.8035	0.0317
14	Enters the Vermillion River at River Mile 15.43	1.8658	0.0067
15	Enters the Vermillion River at River Mile 16.18	0.2635	0.0009
16	Enters the Vermillion River at River Mile 19.06	26.3731	0.0949
17	Upper Vermillion watershed below the MCES gage	2.4068	0.0087
18	Upper Vermillion watershed above the MCES gage	277.98	1.0000

Table 4-5. Estimated Mean Flow to the Vermillion River, 1994-2002

Description	Area (mi^2)	Ratio of Drainage Area to Gaged Drainage Area	Estimated Mean Flow (cfs)
Floodplain of the LVR (ID 1)	18.61	0.0669	10.2
Upland tributaries below Etter Bridge (ID 2–11)	15.93	0.0573	8.7
Upland tributaries between Etter Bridge and Vermillion Slough (ID 12–15)	14.80	0.0532	8.1
Upland tributaries between Vermillion Slough and Hastings (ID 16–17)	28.78	0.1035	15.7
Upper Vermillion River at MCES gage, Hastings, MN	277.98	1.0000	151.9
Total	356.1	1.2809	194.6

4.1.5 Stage and Discharge in the LVR

Flow in the LVR is not gaged, which presents problems for understanding the water balance and movement of pollutants in the system. MPCA has proposed that flow through the LVR can be estimated from a stage-discharge curve at Etter Bridge (Figure 4-25); however, only a limited number of sporadic stage measurements, in 1997 and 1998, have been made at Etter Bridge. This section examines the relationship between stage at Etter Bridge, stage in two LVR lakes, and stage in the Mississippi River.

Tetra Tech obtained USGS stage data for Clear Lake and Sturgeon Lake for October 1998 through September 2002 (Figure 4-25). Some earlier stage data for Clear Lake for July–September 1998 (in a different datum) were provided by Scot Johnson (MPCA). Clear Lake is closely connected with the Lower Vermillion, while Sturgeon Lake (east side of Prairie Island) is tied to Mississippi Pool 3. An important topic for investigation is whether Clear Lake stage, which is continuously recorded, might provide an approximation of stage in the LVR at Etter Bridge, for which only sporadic stage data are available. If so, this would provide a means to reconstruct the LVR flow at Etter Bridge for 1998–2002. Unfortunately, it appears that Clear Lake is not at a level pool with the LVR and thus does not provide a direct indication of stage in the river.

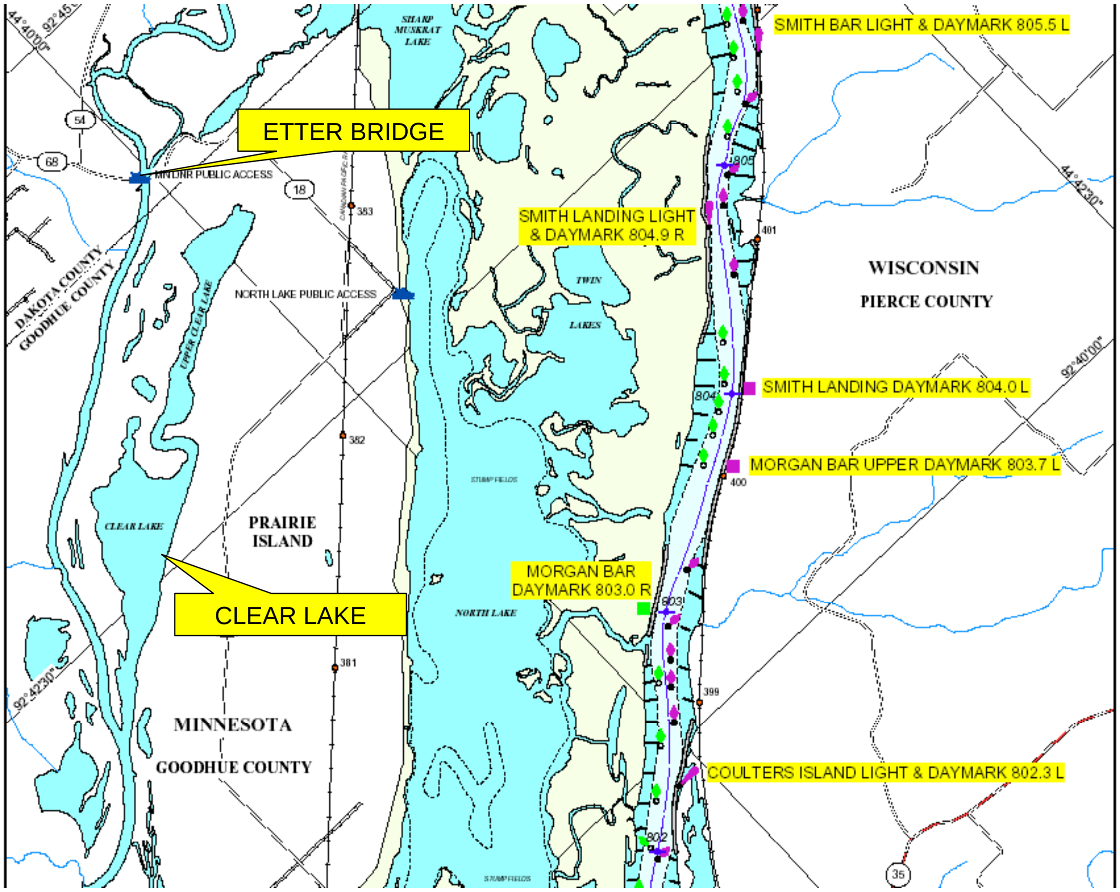


Figure 4-25. Source: Detail from USACE. Mississippi River chart no.14.Location of Etter Bridge and Clear Lake on the LVR .

4.1.5.1 Elevation Datum

Considerable confusion can result from the use of different base elevation references. The USACE manages water levels in the navigational channel of the Mississippi in reference to the National Geodetic Vertical Datum (NGVD) of 1912, despite the fact that this datum has been superseded. As a result, NGVD 1912 is the default reference frame for work in this area, and elevations in other references are converted to NGVD 1912. Other commonly used reference frames include NGVD 1929, which is 0.5 foot lower than NGVD 1912 and is the basis for current topographic maps of the area. More recent work by USGS uses the North American Vertical Datum of 1988 (NAVD 1988), which adjusted to achieve a match between U.S., Canadian, and Mexican reference frames and does not have a constant conversion. Overlap between the two elevation series for Clear Lake indicates a local conversion of NGVD 1912 = NAVD 88 + 0.31 foot.

Individual elevation/stage series have the following characteristics:

- Mississippi Stage Records were collected by USACE and are all reported in NGVD 1912.
- Clear Lake and Sturgeon Lake USGS elevations for October 1998 through September 2002 are in NAVD 1988, as documented in the tabular report provided with the data retrieval. Subtracting 0.31 foot from these records converts then to NGVD 1912.
- Clear Lake data from July 29, 1998, through January 26, 2000 provided by Scot Johnson were reportedly obtained from the USACE and give elevations in NGVD 1912. Adding 0.31 foot to the Clear Lake elevations in this file matches USGS results for the period of overlap.

- Etter Bridge elevation data for 1997 and 1998 were obtained from MPCA and are reported in a memorandum from Scot Johnson to Steve Heiskary, January 22, 1999 (Johnson, 1999). Both stage and elevation are provided, and the elevations are stated to be in NGVD 1912. Confusion over interpretation arises because a memorandum of March 11, 1998, from Scot Johnson to Steve Heiskary states that the Etter Bridge staff gage "has been surveyed in to the Dakota County Bench Mark on the bridge. Gage Zero is 665.69 (1912 NGVD)." However, the reported elevations are equal to the stage plus a gage datum of 665.19. Initially, it appeared that the elevations might actually be in NGVD 1929 (converted from NGVD 1912 by subtracting 0.5 foot). It was later determined that the elevations are correct and in NGVD 1912, but there was a typographical error in the March 11, 1998memorandum regarding the Gage Zero, which should have been stated as 665.**1**9 (Scot Johnson personal communication to Matt Kocian, February 4, 2004).

- A few additional stage records at Etter Bridge, as well as at Larson and Clear Lakes, were obtained by USGS as part of a groundwater quality study for the Prairie Island Indian Community (Winterstein, 2000). These elevations are referenced to "mean sea level" and are apparently in NAVD 1988. Samples were collected on three dates in 1999. Unfortunately, the water level altitude reported for Etter Bridge on February 26, 1999 (693.62 feet) appears to be entered incorrectly because elevation in Pool 3 was around 675 feet at this time, elevation below Lock and Dam 3 was around 669 feet, and elevation at Larson Lake was around 668.77 feet. The other two data points (from May and July 1999) appear to be valid. These points are useful because they correspond to higher flow conditions in the Mississippi, overlap with the Clear Lake record, and provide information on the gradient between Etter Bridge and Larson Lake.

4.1.5.2 Stage-Discharge Relationships at Etter Bridge

Etter Bridge is near the Dakota and Goodhue county line on the LVR . It is a road crossing for County Highway 68 (0). The Dakota County Department of Transportation reconstructed the bridge in 1995, replacing the then existing 150–foot 1-span "H" truss with a 5-span concrete bridge (Figure 4-27). The major slough connections between the LVR and the Mississippi River are all upstream of the bridge location, and the bridge abutments provide one of the few opportunities in the LVR to obtain a stage-discharge relationship, which makes it important to estimate flow accurately at the bridge for overall LVR water balance.

Figure 4-26. Etter Bridge, November 20, 2003.

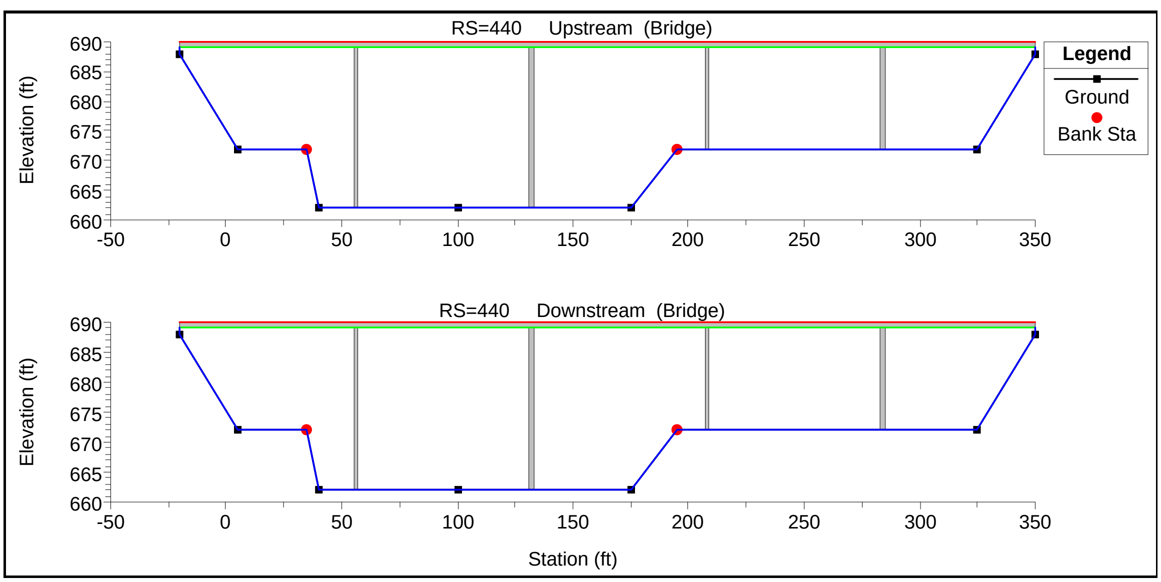


Figure 4-27. Etter Bridge geometry.

Discharge measurements were taken at Etter Bridge in 1992 by the Minnesota Department of Natural Resources (Johnson, 1996), but the corresponding stage data have not been located. The measured flows are presented in Table 4-6. Given the fact that bridge reconstruction has changed the local hydraulics, the stage-discharge data from before to 1995 are of limited relevance. The stage and discharges were measured through staff gage sporadically in the summers of 1997 and 1998 (Johnson, 1999). The data are included in Table 4-6, and were used for deriving the rating curve for the location. A polynomial regression was performed using discharges and gage height readings ($R^2 = 0.99$). The result is plotted in Figure 4-28, and estimated flows are included in Table 4-6.

Table 4-6. Etter Bridge Available Stage and Discharge Data with Estimated Discharge

Date	Staff Gage Reading (ft)	Stage (NGVD 1912, Datum 655.19)	Measured Flow (cfs)	Regression Estimated Discharge (cfs)	Error (Percent)	HEC-RAS Model Simulated Elevation	Lock and Dam 3 Tailwater
12 Jun 97	4.7	669.89	231	285	23.40	670.29	669.87
11 Jul 97	8.88	674.07	1944	1790	-7.92	N/A	673.14
25 Jul 97	10.19	675.38	2369	2581	8.94		673.79
31 Jul 97	11.28	676.47	3412	3328	-2.46		674.81
15 Aug 97	5.3	670.49	419	390	-7.03	671.05	670
25 Sep 97	4.25	669.44	230	235	2.00	669.78	669.15
28 May 98	4.82	670.01	267	303	13.33	670.47	669.95
3 Aug 98	3.89	669.08	213	212	-0.43	669.33	668.53
17 Aug 98	3.54	668.73	221	206	-6.84	669.08	667.82
8 Sep 98	3.43	668.62	230	207	-9.92	669.13	667.77
24 Apr 92	No stage data available		1508	N/A			
17 Aug 92			138				
15 Sep 92			113				

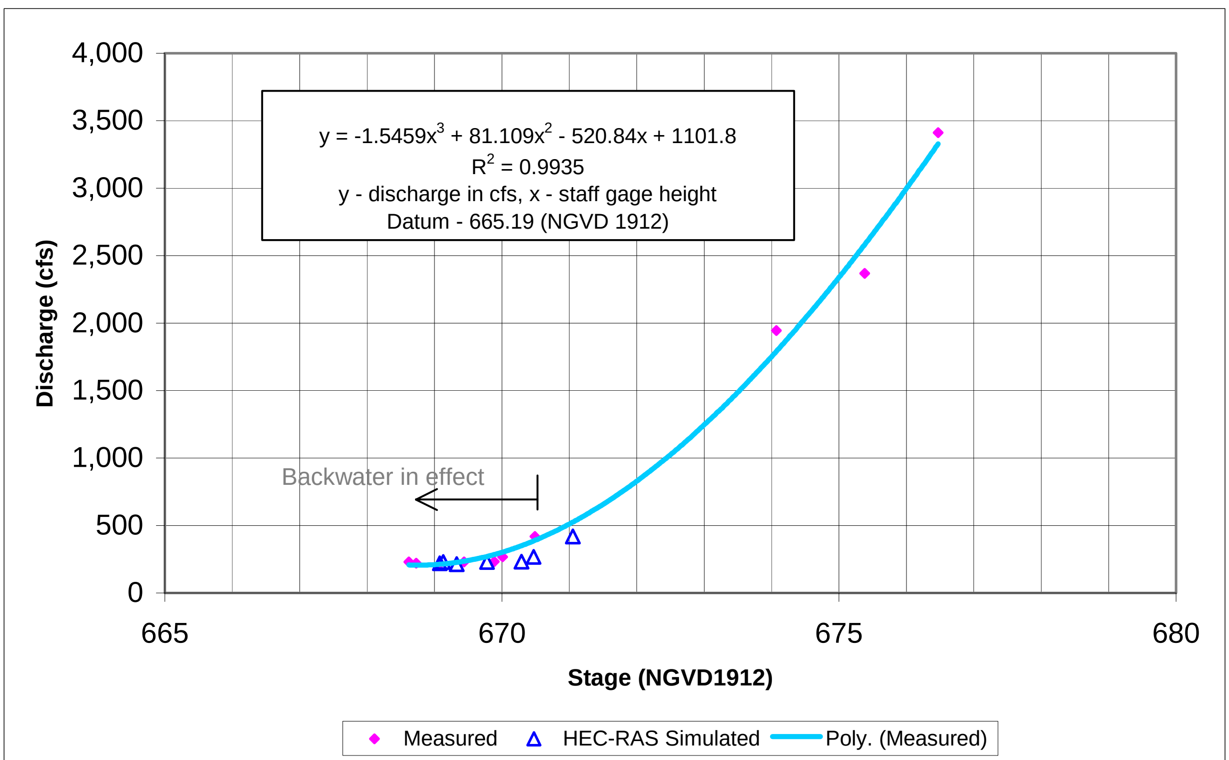


Figure 4-28. Stage-discharge relationship at Etter Bridge.

The regression equation can predict the flow fairly well under high-flow conditions. However, because of the backwater effect from the Mississippi and Cannon rivers, the derived rating curve does not predict the discharge accurately. The backwater effect results in non-uniqueness of the stage-discharge relationship, meaning that the same discharge can occur at different stages. As shown in Table 4-6, a discharge of 230 cfs was measured at elevation 669.44 (NGVD 1912) on September 25, 1997, and at 668.62 (NGVD 1912) on September 8, 1998. The higher water level downstream in the Mississippi River (669.15 at Lock and Dam 3 tailwater) on September 25, 1997, backed up the hydraulic profile higher and the flow velocity was lower. Therefore, it might not be appropriate to derive a single rating curve for low-flow conditions when backwater is in effect.

The purpose of establishing a stage-discharge relationship is to predict flows for given stages. Because the unique curve cannot be developed for low-flow conditions, more frequent flow measurement should be made or a hydraulic/hydrodynamic model needs to be uses to interpret low-flows correctly. A preliminary 1-D hydraulics HEC-RAS model was developed to evaluate the backwater effect from the downstream end of the LVR. The measured flow and Lock and Dam 3 tailwater level are used as inputs. The channel geometry is extracted from recent sounding data. The model results are shown in Table 4-6 and Figure 4-28. Though the model is not rigorously calibrated, it simulated the stages at Etter Bridge reasonably. This simple exercise explains that 1-D profile simulation, coupled with stage records at several locations along the LVR, can be used to interpolate flows at both low-flow and high-flow conditions in the LVR. An additional finding is that the bridge opening does not appear to restrict flow significantly.

4.1.5.3 Relationship of Clear Lake and Etter Bridge Water Surface Elevation

Elevation records at Clear Lake and MPCA measurements at Etter Bridge overlap for 10 observations in July-September 1998, which was a period of relatively low-flows. These data provide only a limited basis on which to infer the relationship between these gages. The 10 concurrent measurements are plotted against one another in Figure 4-29. For this limited period of data, water surface elevations at Clear Lake are always greater than elevation at Etter Bridge, despite the fact that Clear Lake is connected to the LVR downstream of Etter Bridge.

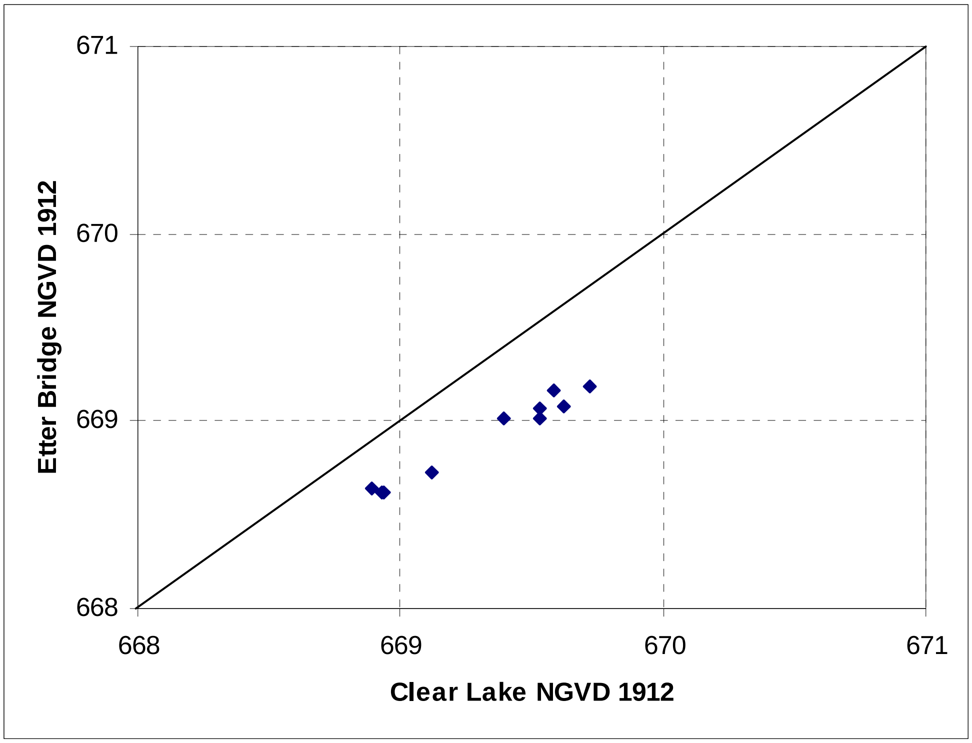


Figure 4-29. Comparison of Etter Bridge and Clear Lake water surface elevations, July-September 1998

The relationship shown in Figure 4-29 indicates that there was a positive gradient from Clear Lake to the LVR, at least during the dry weather of summer 1998. This fits with anecdotal information provided by Scot Johnson, who estimated that there was a flow of about 20 cfs coming from Clear Lake to the LVR during this period. This flow might have derived from groundwater flux from Pool 3, which was at an elevation about 6.5 feet above the level of Clear Lake during this period. Cowdery (1999) evaluated water table elevations around Prairie Island and concluded that there was significant and rapid groundwater flow between Pool 3 and the LVR. On the north side of Prairie Island, Sturgeon Lake and North Lake are hydrologically connected to Pool 3, creating a large head drop over the short distance to the LVR, and the subsurface material contains plentiful sand and gravels that promote flow. In addition, a DNR Stream Survey Report (Dieterman, 1995) notes, "Substantial groundwater seepage is common along much of the north shoreline" of Clear Lake, while in Upper Clear Lake "groundwater seepage and spring flows along the northwest and north shorelines are substantial enough to maintain areas of open water throughout much of the winter."

For this period of overlapping records, Clear Lake was not at level pool with its connection point to the LVR; instead, stage in Clear Lake was almost exactly 0.5 foot above elevation at Etter Bridge. This relationship, however, cannot safely be assumed to hold during other flow conditions. The two USGS observations from 1999 provide information on the relative elevation at higher flow conditions. On May 15, 1999, Etter Bridge was at 678.66feet (NGVD 1912) and Clear Lake at 676.29 feet, while on July 7, 1999, Etter Bridge was at 672.74 feet and Clear Lake at 672.32 feet. Thus, at elevated flow the gradient is from Etter Bridge to Clear Lake.

As a result of the low-flow elevation differences, the Clear Lake water surface elevation record cannot be used directly to estimate stage in the LVR at Etter Bridge or elsewhere.

4.1.5.4 Hydrologic Behavior

Assembly of the water surface elevation records allows a number of general insights into the hydrologic behavior of the LVR system. All elevations were converted to a consistent basis in NGVD 1912 for comparison, as described above. Clear Lake elevations were assembled from the USGS data, plus earlier data contained in LVR.WDM. Figure 4-30 compares stage in Clear and Sturgeon Lakes with stage in the Lock and Dam 3 Pool and stage at Prescott, further upstream in Pool 3 elevation. Sturgeon Lake elevation remains very close to Lock and Dam 3 Pool elevation at all times. At lower flow, Clear Lake elevation is always lower than Sturgeon Lake or Pool 3. During high flow, water surface elevation in both Clear Lake and Sturgeon Lake rises following the pattern in Mississippi Pool 3 at Prescott.

Figure 4-31 compares stage in Sturgeon Lake and Clear Lake. During low-flow, stage in Sturgeon Lake is about 5 feet above Clear Lake. During flood flow in the Mississippi, stage in both lakes converges, indicating that the water level is being controlled by the Mississippi.

Figure 4-32 compares elevation in Clear Lake to the various stage gages in the Mississippi. During moderately low-flow, elevation at Clear Lake appears to be controlled by the Lock and Dam 3 tailwater elevation, presumably because of backwater in the LVR. During the driest period, however, there is a gradient from Clear Lake to Lock and Dam 3 tailwater, likely reflecting groundwater seepage, as noted above. During high flow, stage at both Clear Lake and Lock and Dam 3 tailwater appears to be driven by the stage farther up Pool 3 (Prescott), reflecting large inflows of water into the LVR system through the sloughs.

Water surface elevations at Etter Bridge for 1998 are compared to elevations in Clear Lake and at Lock and Dam 3 tailwater in Figure 4-33. In the early summer the Etter Bridge water surface elevation tracks well with the Lock and Dam 3 tailwater stage. For the late summer period of 1998, the Etter Bridge water surface elevation is less than that of Clear Lake, but greater than the Lock and Dam 3 tailwater elevation. It appears likely that the system is constrained to prevent the elevation from falling much below about 668.6 feet. One possible explanation is the existence of shallower channel nickpoint controls downstream. In addition, drop below this level is limited by high water table elevations; Cowdery (1999) reports the normal water table surface at Larson Lake as 668.68 NGVD 1912.

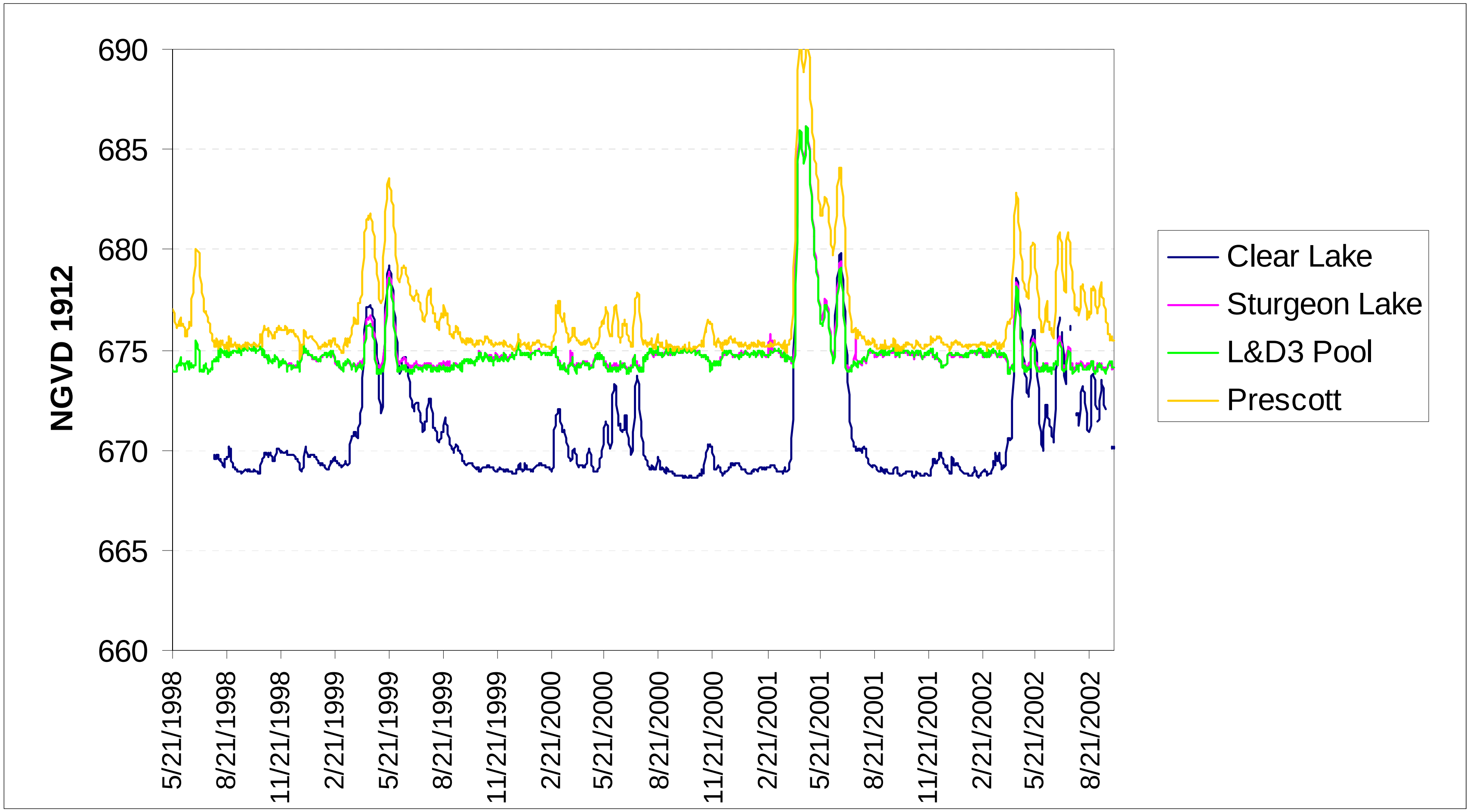


Figure 4-30. Comparison of Clear Lake and Sturgeon Lake elevations to Mississippi gages.

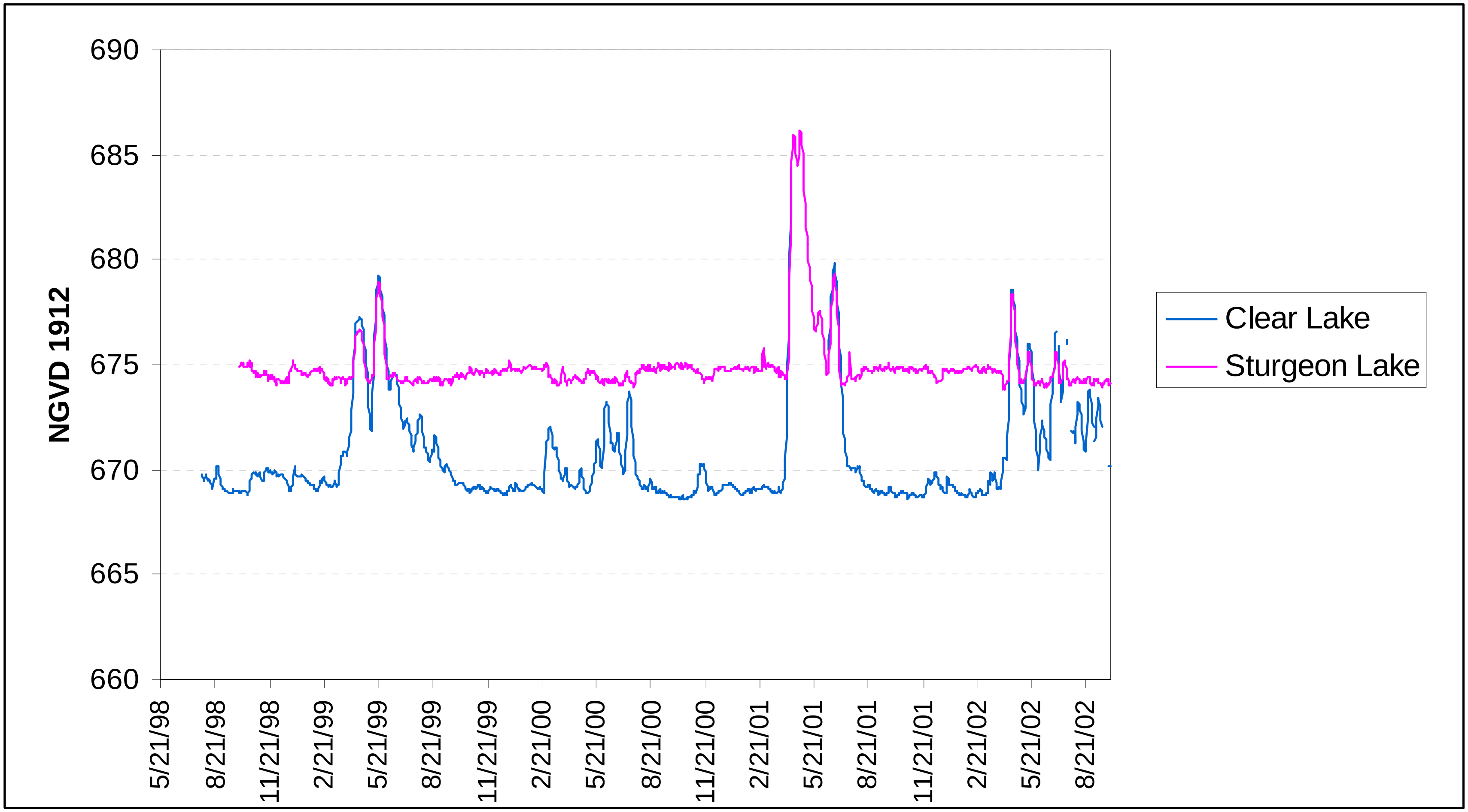


Figure 4-31. Comparison of Clear Lake and Sturgeon Lake elevations.

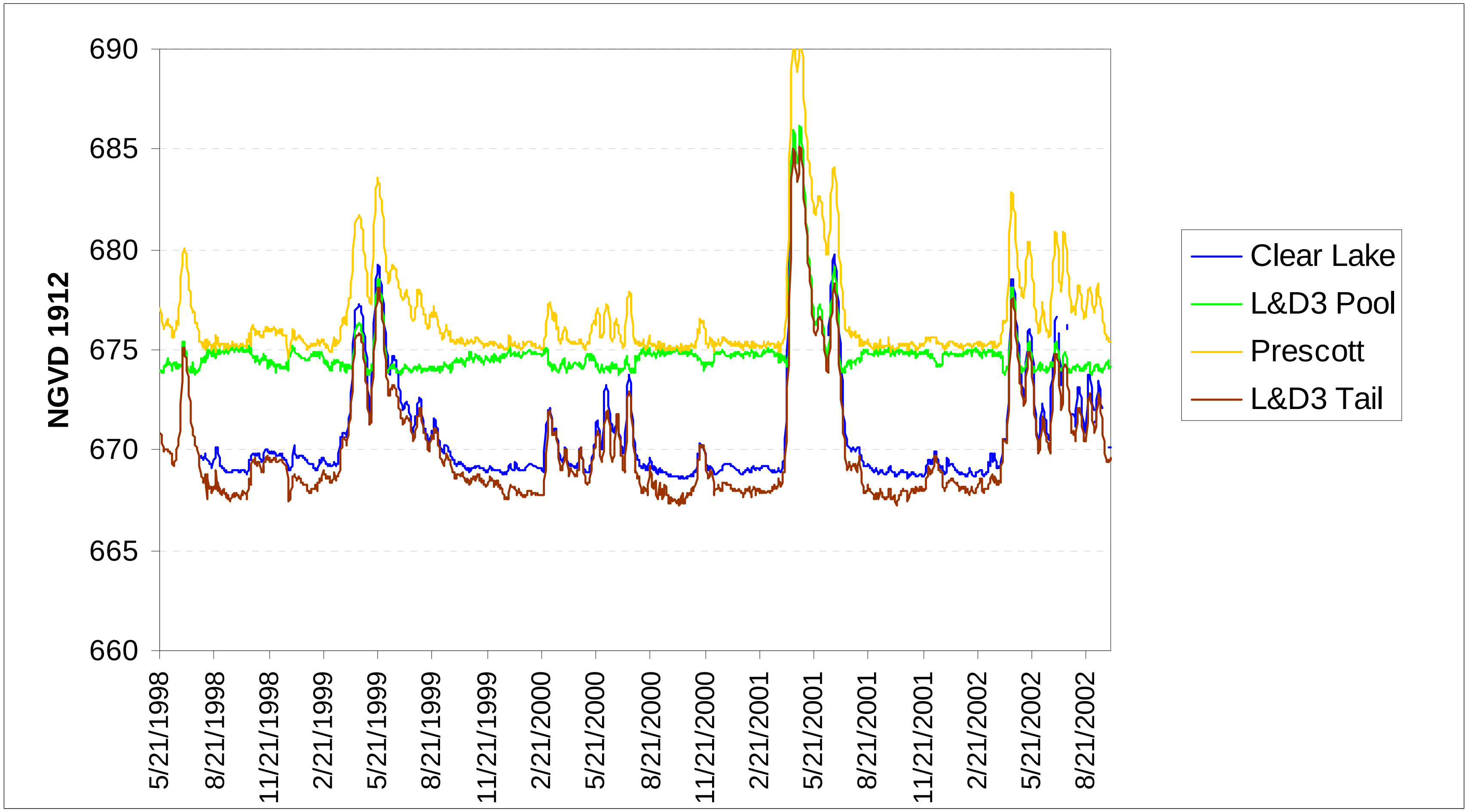


Figure 4-32. Comparison of Clear Lake and Mississippi elevations.

Figure 4-33. Comparison of Etter Bridge elevations to Clear Lake and Lock and Dam 3 tailwater elevations, 1998.

Elevations recorded by USGS in 1999 are shown in Table 4-7, along with USACE elevations for the Lock and Dam 3 tailwater. The measurements from May and July 1999 represent fairly high flow conditions, and show drops in head from Etter Bridge to Lock and Dam 3 tailwater of 3.7 and 1.1 feet, respectively. The February measurements (for which the Etter Bridge elevation does not appear to be valid) occurred during relatively low water in the Mississippi, but a head drop of 0.35 foot was still present between Larson Lake and the Lock and Dam 3 tailwater.

Table 4-7. Water Surface Elevations for Vermillion River at Etter Bridge, Larson Lake, and Lock and Dam 3 Tailwater, 1999 (NGVD 1912)

Date	Etter Bridge	Larson Lake	Lock and Dam 3 Tailwater
2/26/99	--	669.08	668.73
5/15/99	678.66	677.55	674.90
7/9/99	672.74	671.79	671.64

Figure 4-34 compares the full set of 1997–1999 Etter Bridge water surface elevations to elevations in the Mississippi. For most of the data points, the Etter Bridge elevation is very close to the Lock and Dam 3 tailwater elevation. This suggests a backwater condition at Etter Bridge that limits usefulness of a stage-discharge curve at this location. Divergences from Lock and Dam 3 tailwater elevation occur during high elevations in Pool 3 and at very low elevations in the Lock and Dam 3 tailwater. Under both conditions a gradient exists from Etter Bridge to Mississippi Pool 4.

The hydrologic behavior observed at higher flows is controlled in large part by the sloughs and diking between the LVR and Mississippi Pool 3. When Pool 3 is above the elevations of the controlling dikes, inflow to the LVR occurs and a positive flow is established toward Pool 4. This would also occur when flows in the Upper Vermillion are high. However, when the Lock and Dam 3 tailwater rises above about 675.3 (which appears to correspond to an elevation at Prescott of about 678 feet), the drop across Lock and Dam 3 is minimized, reducing the head for flow from Pool 3 into the Vermillion. As a result, during the high flow period of April–May 1997, elevation at Etter Bridge was again nearly equal to elevation at the Lock and Dam 3 tailwater and subject to backwater effects.

The discussion above is based on limited observations and needs to be confirmed with additional data. The observations available from 1997–1999 suggest, however, that the primary controls on the flow regime in the LVR are as summarized in Table 4-8.

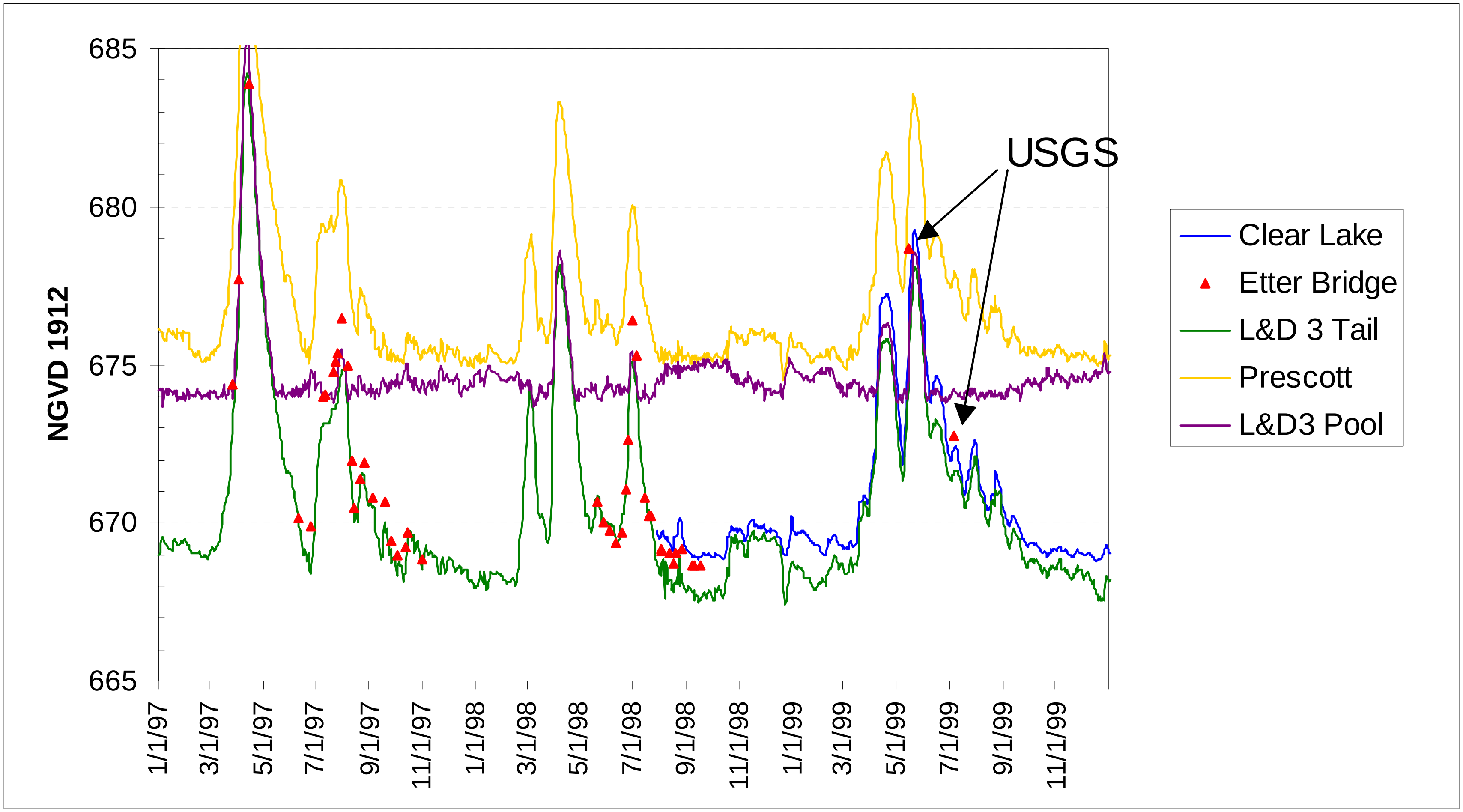


Figure 4-34. Comparison of Etter Bridge and Mississippi River elevations, 1997–1999.

Table 4-8. Draft Analysis of Flow Regime Controls in the LVR

Elevation at Prescott (NGVD 1912)	Elevation at Lock and Dam 3 Tailwater (NGVD 1912)	LVR Flow Regime
< 675.3	< 668.6	Flowing with stage controlled by channel obstructions
< 675.3	668.6 – 675	Stage controlled by Pool 4 backwater
> 675.3	669 – 675	Inflow from Pool 3 establishes free-flowing conditions to Pool 4
> 678	> 675	Inflow and through-flow limited by Pool 4 backwater

4.1.6 Conceptual Model of LVR Hydrology

4.1.6.1 Interchange with the Mississippi River

The hydrology of the LVR is complex because of the interchange of water between the LVR and Mississippi Pool 3. This interchange depends on the relative stage in the two systems. At a gross conceptual level, four modes of behavior can be distinguished: Normal Flow, Mississippi High Flow, Upper Vermillion High Flow, and Cannon River Flood. These four modes summarized graphically in Figure 4-35 and Figure 4-36, are distinguished by different modes of interaction with the Mississippi. As noted in Section 4.1.2.5, stage in Pool 3 is low enough to prevent flow from the Mississippi to the LVR about 50 percent of the time (Mode 1). Above this level, flow can enter the LVR from Pool 3, first via Vermillion Slough, then via Truedale and Carter Slough (Mode 2). High water in the Upper Vermillion (Mode 3) may cause a reversal of flow through Vermillion Slough. Finally, elevated stage below Lock and Dam 3, or flood flows in the Cannon River, can cause a backwater with reversal of flow into the downstream end of the LVR.

Sufficient data are not yet available to complete a quantitative analysis of flow between the LVR and Mississippi (see Section 4.1.6.2). An order of magnitude estimate can be made, however, by using the preliminary stage-discharge estimates for the sloughs presented in Section 4.1.2. Preliminary estimates of potential inflow based on Pool 3 stage are shown in Table 4-9. The table includes flows from Vermillion and Truedale sloughs, but not Carter Slough, because no stage-discharge relationship for Carter Slough has been developed; however, flow through Carter Slough is likely to be small relative to the other connections because the dike is higher and the connection less direct. The flow regime cannot be defined above a Prescott stage of 682 feet at this time (the upper 4.5 percent of the distribution) because this results in general flooding of the area between the LVR and Mississippi south of Hastings.

Figure 4-37 shows the inflow distribution graphically. Below 50 percent of the Prescott stage distribution, the only surface inflow to the LVR is through the Truedale Culvert. Above this level, flow through the sloughs increases exponentially, reaching an estimated value of 7,700 cfs at a Prescott stage of 682 feet. In contrast, the average flow from the Upper Vermillion is 151.9 cfs. Integrating over the potential inflow distribution up to stage of 682 feet, the average inflow from Pool 3 to the LVR is 615 cfs, or about four times the inflow from the Upper Vermillion. Most of this inflow, however, occurs in the upper 25 percent of the Prescott stage distribution.

In sum, on a long-term basis the LVR system appears to receive significantly more inflow from Mississippi Pool 3 than from the Upper Vermillion. Even when estimates of inflow from local tributaries to the LVR and groundwater discharge (probably on the order of 100 cfs) are added, the long-term inflow from Pool 3 is still more than twice the flow from other sources. Cumulative loading to the LVR (of water and pollutants) thus depends largely on the Mississippi. During low to moderate flow conditions, however, inflow to the LVR can be dominated by it's the river's own watershed.

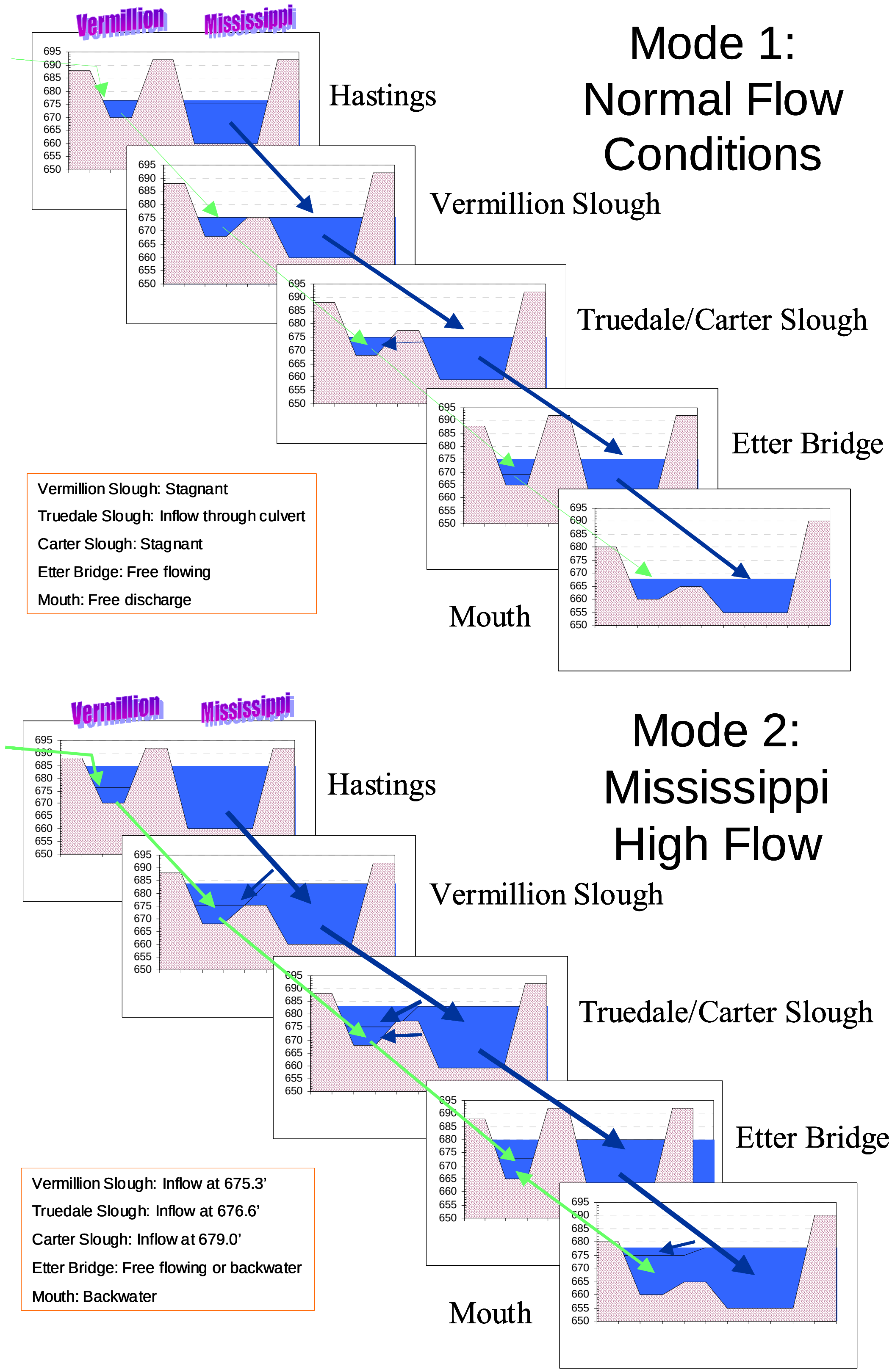


Figure 4-35. Conceptual model of LVR hydrology, Modes 1 and 2.

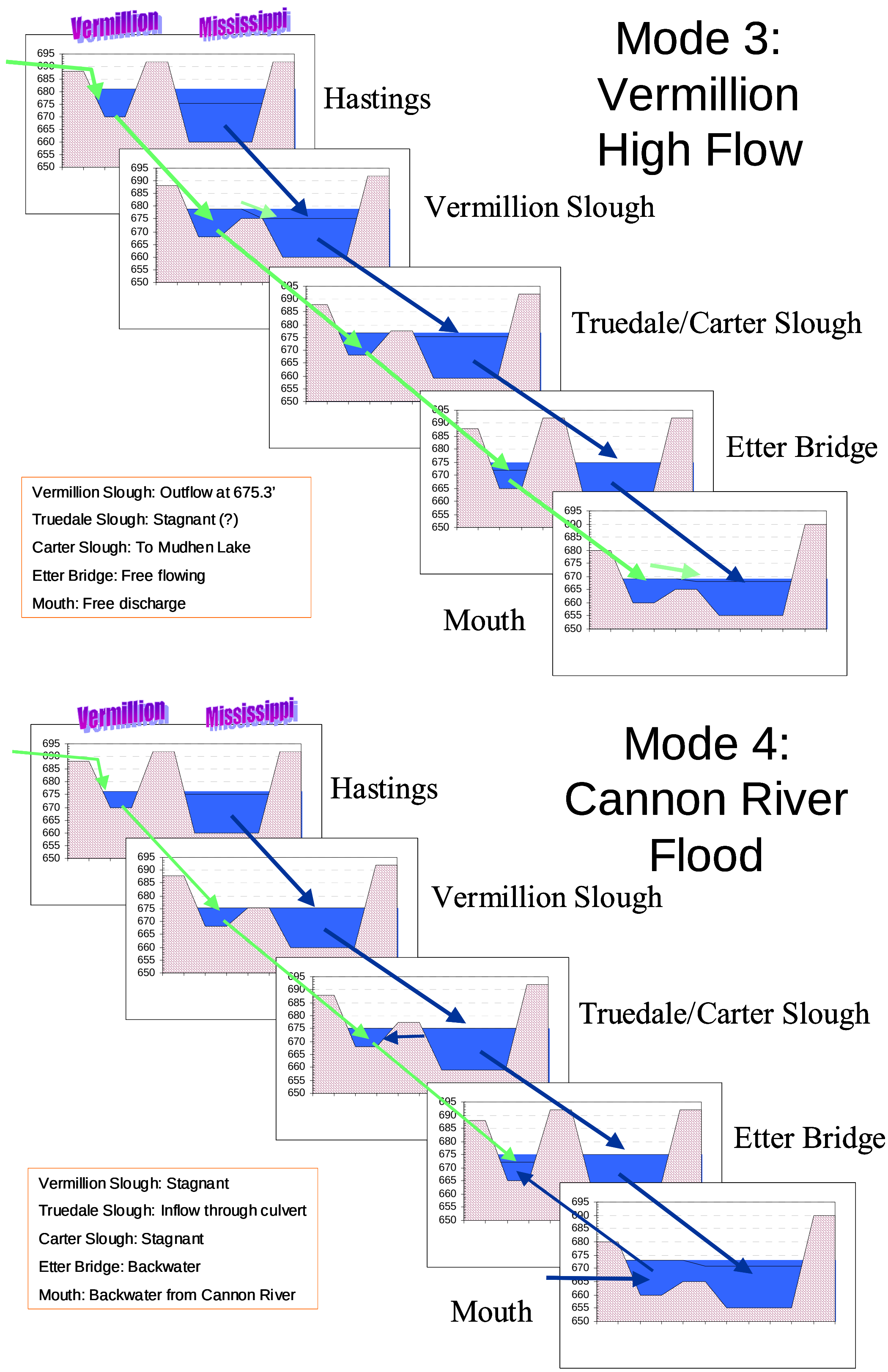


Figure 4-36. Conceptual model of LVR hydrology, Modes 3 and 4.

Table 4-9. Preliminary Estimates of Inflow to the LVR from Mississippi Pool 3 (cfs)

Prescott Stage	Cumulative Percent	Vermillion Slough	Truedale Culvert	Truedale Slough	Total Inflow
<674	1.46	0	40	0	40
<675.3	55.23	0	50	0	50
<675.5	61.33	12	50	0	62
<676.78	75.78	257	50	0	307
<680	77.06	317	55	0	372
<677.5	79.82	471	58	150	679
<678	82.49	646	62	300	1008
<678.5	84.74	841	66	600	1507
<679	86.67	1055	70	828	1953
<679.5	88.55	1287	72	1428	2787
<680	90.28	1536	74	1700	3310
<680.5	91.84	1803	75.1	2424	4302.1
<681	93.09	2086	79	3200	5365
<681.5	94.28	2386	83	4415	6884
<682	95.47	2703	100	4915	7718
<690	99.92	?	?	?	?
<700	100.00	?	?	?	?

Note: Estimates for Truedale Culvert and Slough assume a culvert invert elevation of 671 feet (NVGD 1912) and a tailwater of 672 feet for Prescott stage through 679 feet, 674 feet for Prescott stage of 680 feet to 682 feet, and 678 feet for Prescott stage greater than 682 feet. Estimates for Vermillion Slough are provisional and do not account for effects of any residual grade control at the Three Bridge Dike site. Estimates of flow through Carter Slough are not yet available but are expected to be significantly less than for Truedale Slough. Flow regime at Prescott stage greater than 682 feet is not yet defined.

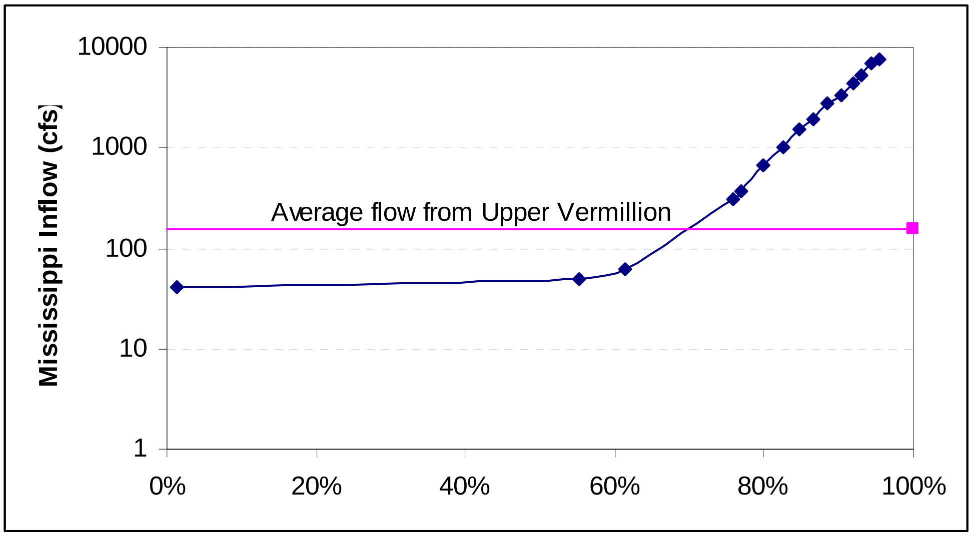


Figure 4-37. Mississippi Inflow to the LVR versus percentiles of Prescott stage.

4.1.6.2 Conceptual Approach to Hydrologic Modeling of the LVR

Sufficient data are not available at this time to complete a quantitative model of the hydrology of the LVR. However, a conceptual understanding of the system has been established, and it allows description of the methods that could be used to develop such a model in subsequent phases of the project.

The purpose of developing a hydrologic model of the LVR is to quantify flows into and out of the system to provide a basis for constructing the mass balances of sediment and other pollutants. Because of the dikes, levees, and control structures on the Mississippi River as it parallels the LVR, many hydrologic interactions affect flows in the LVR. For approximately 20 miles, the LVR flows through the floodplain of the Mississippi. The two rivers are connected by three major sloughs with control structures; it is expected that numerous smaller channels also connect the two systems, but these flows are not regulated by control structures. The operation of lock and dam structures on the Mississippi (e.g., Lock and Dam 2, Lock and Dam 3, and Lock and Dam 4), and connections with lakes can create backwater effects that prevent the LVR from acting as a free-flowing system. To adequately describe flows, the LVR will be generally considered as two reaches, separated near the Etter Bridge crossing (approximately 9.5 miles upstream from the mouth). The location of Etter Bridge is of interest because the three major sloughs—Vermillion, Truedale, and Carter—connect the LVR and the Mississippi upstream of this point. No flow monitoring data are available for the three sloughs, so the flows need to be evaluated using the stages of the Mississippi River and the LVR. A stage-discharge relationship is available for the LVR at Etter Bridge, which will help establish flows in the LVR upstream of the bridge.

The channel slope of the LVR for the lower 13 miles, in which the Etter Bridge crossing is included, is essentially flat. Therefore, the stage of Lock and Dam 3 tailwater can be used to determine the stage in the lower reaches of the LVR for stages greater than 668.7 (NGVD 1912). When the stage at Lock and Dam 3 tailwater drops below 668.7 feet, the stage at Etter Bridge does not show a corresponding drop, as evidenced by the stage-discharge curve. Debris in the channel, natural grade control, and groundwater likely interact to prevent the stage at Etter Bridge from dropping below 668.7 feet. When the stage of the Lock and Dam 3 tailwater drops below 668.7feet, a positive gradient exists through the LVR downstream of Etter Bridge, so outflows will be considered equal to inflows. When the stage is between the 668.7 feet and approximately 675 feet (a general estimate of the elevation of the top of the LVR banks and the approximate elevation of the Vermillion dike crest), the stage-discharge rating curve at Etter Bridge will be used to approximate discharge. If the stage recorded at the Prescott gage on the Mississippi allows for flow over the control dikes into the LVR through the sloughs, a positive gradient to the Lock and Dam 3 tailwater will occur. If the stage at Prescott does not provide flow into the LVR system through the sloughs, the flow in the LVR will be controlled by the Lock and Dam 3 tailwater. When the stage at Lock and Dam 3 tailwater exceeds the top of banks in the LVR, outflows will be considered to equal inflows. When the Mississippi at Prescott overtops the levees into the LVR, the entire Mississippi floodplain is inundated and flows will be controlled by the Mississippi.

There are Two options for completing a hydrologic model of the LVR. One is the development and calibration of a dynamic hydraulic model capable of addressing bidirectional flow at control structures, such as the Environmental Fluid Dynamics Code (EFDC). Development of a complex hydrodynamic model might not be warranted, however, if the primary concern is balancing flows and pollutant loads at the daily (or longer) time scale. A hydrologic and pollutant balance of this sort could be developed using a simpler approach that conserves mass but not momentum.

The following is a conceptual framework proposed for this simpler type of modeling of the LVR hydrology. A time increment of 1 day will be set because most of the monitoring data are available as daily averages (e.g., stage and discharge). Initially the stage at Lock and Dam 3 tailwater will determine the stage at Etter Bridge. If the Lock and Dam 3 tailwater stage is less than 668.7 feet, the stage at the bridge will be set to 668.7 feet; if the Lock and Dam 3 tailwater stage is greater than 668.7 feet, a level pool backwater will be assumed to set the stage at Etter Bridge. The available stage-discharge relationship can equate discharges in the LVR with the stage (between 668.7 and 676.5). The average daily flow of the Vermillion River at Hastings will be used to establish a preliminarily water surface profile in the Vermillion River between the confluence with the Vermillion Slough (approximately river mile 19.0) and Etter Bridge (approximately river mile 9.5). The initial water surface profile of the LVR will be compared to the stage in the Mississippi at Prescott (minus given amounts to account for river slope to the Truedale and Carter sloughs) to determine the direction and magnitude of flows across the dikes, if any. The flow over the dikes will be calculated using equations developed for broad-crested weirs for both modular and submerged flows. It appears that the Vermillion Slough is the only slough where flow over the control structure might be bidirectional. Any calculated flow in the sloughs will be added to or subtracted from the LVR flow to update the elevation of the water surface profile. In addition, inflows will need to be estimated for local tributaries (presumably using a simple watershed model) and from groundwater (based on aquifer transmissivity and the head difference between Pool 3 and the LVR). In this fashion, the stage from the previous time step will be used to calculate flows through the sloughs on a given day. The water surface profile and corresponding stages will be updated based on the flows. The updated stage will be used with the stage-discharge relationship at Etter Bridge to determine the average daily flow through the upper reach of the LVR. Coupled with the level pool or free-flowing conditions in the lower reach of the LVR, this methodology will allow the flows into and out of the LVR each day to be quantified. The flow series can then form the basis for driving a water quality model.

4.2 LVR Turbidity

4.2.1 Relationship of Turbidity to Suspended Solids and Algae in the LVR

Turbidity is a measure of water clarity that refers to the scattering of light by suspended matter, dissolved organic compounds, and plankton in the water. If water becomes too turbid, it loses the ability to support a wide variety of plants and other aquatic organisms. Suspended particles can also clog fish gills, lowering their resistance to disease, lowering their growth rates, and affecting egg and larval development. The measurement of turbidity is used as an indirect indicator of the concentration of suspended matter and it is also important for evaluating the available light for photosynthetic use by aquatic plants and algae.

Quantifying the relationship between pollutant mass loads and turbidity is a necessary step toward completing the TMDL. As specified in Minnesota water quality criteria, turbidity is measured by the dimensionless nephelometric turbidity unit (NTU), which is a measure of optical light-scattering properties rather than a mass-based concentration. It is not easily interpreted as a mass load in the TMDL framework. Therefore, one of the keys in developing a turbidity TMDL is to establish a cause-and-effect relationship between turbidity and mass-conserving constituents such as TSS and organic matter. Elevated organic matter and algae concentrations are further caused by eutrophication stimulated by excessive nutrient loading.

4.2.1.1 Theory

Relationships between suspended matter concentrations and optical properties of water are highly complex and difficult to resolve mathematically (Gallegos and Neale, 2002); however, it is clear that effects depend on the mass concentration and type of suspended particulate matter. Particulate matter both attenuates and scatters light in the water column. Scattering also increases attenuation as the travel path length per unit depth increases. Nephelometric turbidity measures only the scattering component.

Gallegos (2001) documents an approximately linear relationship between turbidity and TSS at Chesapeake Bay sites, and a linear relationship has also often been noted in the evaluation of dredging operations. The relationship between the inorganic sediment contribution to turbidity and inorganic suspended solids can be generally described by the empirical equation

$$\textit{Turbidity} = \beta \cdot \textit{TSIS}^{\alpha} \qquad (1)$$

where *TSIS* is total suspended inorganic solids, α is a coefficient that is usually in the range 0.7 to 1.0, and β is an empirical fitting coefficient. The USACE has developed method recommendations for evaluating the turbidity-TSS relationship (Thackston and Palermo, 2000). The magnitude of the exponent *a* depends on the sediment size and organic content of suspended matter in the stream. Additional contributions to turbidity are made by algae and dissolved organic compounds, both of which have light-scattering properties somewhat different from those of inorganic solids and might require separate relationships.

Algae contribute to turbidity in different ways from inorganic suspended solids. The wet density of algae is generally much less than that of inorganic solids. Austin (1974) found that light absorbance is inversely proportional to the total surface area of particles in the water, instead of their weight, but that algae scatter light less than inorganic particles of the same size. The effect of algae on water clarity, measured as Secchi disk depth or light transmission, is therefore generally much greater than the effect of algae on turbidity, measured as light refraction with a nephelometer.

In general, algae, measured as chlorophyll *a*, would be expected to provide an additive component to inorganic solids in estimating total turbidity. The relationship given in Equation 1 is, however, properly formed in terms of the suspended inorganic solids. Furthermore, most available data is usually total suspended solids, which includes both inorganic and organic solids, with the latter component including the algae. A relationship of turbidity to TSS (including algae) may thus often have a negative coefficient on algae added as an independent variable because algae scatter light less effectively than do inorganic solids:

$$\textit{Turbidity} = \beta_0 + \beta_1 \cdot \textit{TSS}^{\alpha} - \gamma \cdot \textit{chl-a}. \qquad (2)$$

The intercept term, β_0, represents a residual component of turbidity, due for instance to dissolved organic material or color. Gallegos (2001) did not find it necessary to correct TSS for chlorophyll content in analyzing turbidity in the Chesapeake, but this is likely because of the presence of near-linear correlations between TSS and chlorophyll in his data.

Given that on the order of 2 percent of the dry biomass of algal cells is made up of chlorophyll *a*, the relationship to TSS could also be corrected to remove the algal component:

$$\textit{Turbidity} = \beta \cdot (TSS - 0.05\ Chl\text{-}a)^{\alpha} + \gamma \cdot Chl\text{-}a, \qquad (3)$$

for chlorophyll *a* in micrograms per liter and TSS in milligrams per liter. However, Equation 3 still does not correct for the presence of detrital organic matter. The resulting functional form is also very similar to that given by Equation 2 for typical ambient concentrations. It is therefore preferable to use Equation 2 over Equation 3 when fitting turbidity against TSS and chlorophyll *a*.

A more relevant decomposition for TSS is likely provided by separation into total nonvolatile and total volatile solids components (TNVS and TVS), which are often provided in monitoring data. The nonvolatile component approximates the inorganic solids (although also containing ash residue from organic matter while losing some inorganic minerals), while the volatile component approximates the organic matter contribution, including both algae and detritus. Assuming that the main differentiation in optical properties is between inorganic minerals and organic material, relationships based on TNVS and TVS can be useful for predicting turbidity. Building on the mathematical forms presented above, these relationships could take the form

$$\textit{Turbidity} = \beta_0 + \beta_1 \cdot TNVS^{\alpha} + \gamma \cdot TVS. \qquad (4)$$

An attraction of this approach is that the contribution of algae to turbidity can be resolved given an assumption regarding the algal fraction of TVS (Chesapeake Bay Program, 2000). For instance, if the average dry weight composition of algae is assumed to be 50 mg carbon per mg chlorophyll *a* and carbon mass is assumed to represent 50 percent of the volatile solids contribution of algae (Bowie et al., 1985), the contribution of algae to TVS can be estimated as 0.1 · chlorophyll *a* (for TVS in milligrams per liter and chlorophyll *a* in micrograms per liter). Effects on turbidity of reducing algal concentrations can then be estimated.

4.2.1.2 Correlation of Turbidity, TSS, and Chlorophyll *a*

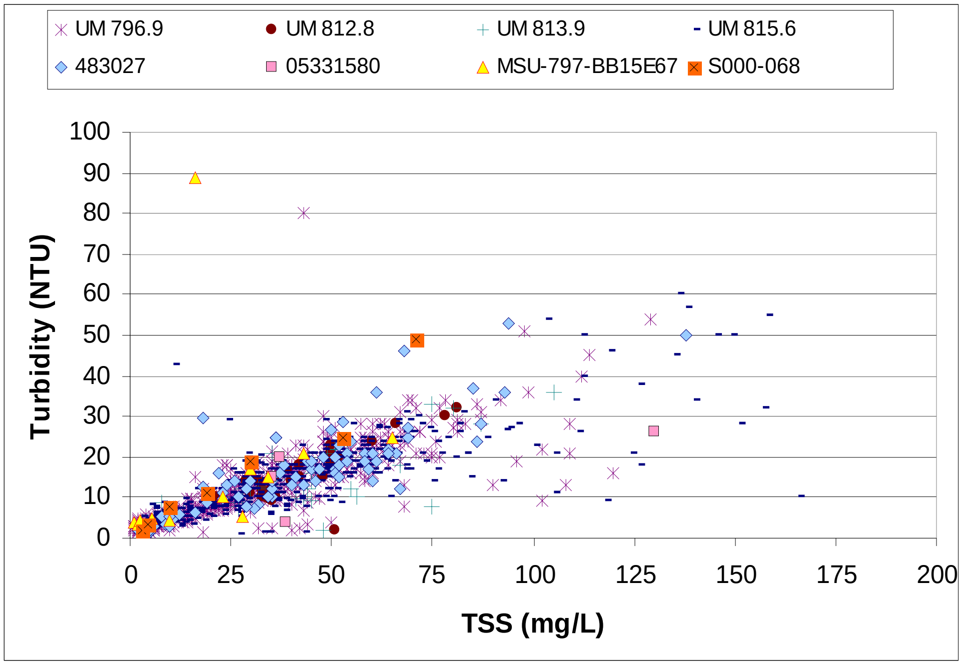
The first step of the exploratory data analysis was to explore the relationships between turbidity, TSS, and chlorophyll *a*. Same-day paired observations of nephelometric turbidity and TSS were queried from the water quality database (including the additional Excel spreadsheets). Older data reported in JTUs were not used. These units approximate nephelometric turbidity units to some degree but use different methodology and are not acceptable for regulatory purposes (Wilde and Gribs, 1998).

In addition to turbidity data, observations of chlorophyll *a* occurring on the same day as the paired TSS-turbidity observations were also retrieved from the database. Stations were grouped into three categories based on general location: Mississippi River Pool 3 (stations 483027, 05331580, MSU-797-BB15E67, S000-068, MR 796.9, MR 812.8, MR 813.9, and MR 815.6), Upper Vermillion River (stations MWCC-055, S001-226), and LVR (stations MS221, MS295, MS297, MS299, S001-193, S001-230, and VM00.1M). Station locations are shown in Table 4-10. Station categories are kept separate in the analysis because sediment character, and thus optical scattering properties, is likely to differ among the three waterbodies. The Upper Vermillion data set consists only of observations at Hastings; just above the Lower Vermillion; the other two categories include multiple sampling stations. Only a few observations of chlorophyll *a* were available for the Upper Vermillion, so no analyses with chlorophyll *a* were performed.

Figure 4-38 through Figure 4-40 show the relationship between these parameters for the three location groups. Turbidity generally appears to be strongly correlated with TSS, but the relationship with chlorophyll *a* concentration is weak at best. Based on a visual examination of the data, it appears that station location within Pool 3 likely had little influence on the relationships between variables. For the Lower Vermillion, all but two samples that contain TSS and turbidity simultaneously are from stations MS221 and VM00.1M, while for the Upper Vermillion all but two samples are from MCES monitoring at MWC0055.

Table 4-10. Monitoring Stations Used in Analyses of Turbidity-TSS Relationships

Category	Station ID	Location
Miss. River Pool 3	483027	Miss River Lock+Dam # 3 Redwing, MN
Miss. River Pool 3	05331580	Mississippi River below Lock and Dam 2 at Hastings, MN
Miss. River Pool 3	MSU-797-BB15E67	Mississippi R Lock and Dam 3, 5 Miles northwest of Red Wing
Miss. River Pool 3	S000-068	Mississippi River at Lock and Dam 2 at Hastings
Miss. River Pool 3	MR796.9	Mississippi River above Lock and Dam 3
Miss. River Pool 3	MR812.8	Mississippi River below Hastings WWTP
Miss. River Pool 3	MR813.9	Mississippi River at Hastings Bridge
Miss. River Pool 3	MR815.6	Mississippi River above Lock and Dam 2
Upper Verm. River	MWCC-055	Vermillion River at CR-47 near Hastings
Upper Verm. River	S001-226	Vermillion River at Hwy 54, 7/8 Mile southeast E of Hastings
Lower Verm. River	MS221	Vermillion River1 Mi upstream of Cannon River confluence Nr Red, WI
Lower Verm. River	MS295	Vermillion River at Hwy 54, 7/8 Mile southeast of Hastings
Lower Verm. River	MS297	Vermillion River southeast 1/4 S5, 5 Miles southeast of Hastings
Lower Verm. River	MS299	Vermillion Rivers at Hwy 68 Bridge, 3/4 Mile northeast of Etter
Lower Verm. River	S001-193	Vermillion River 0.1 Mile upstream Cannon River Confl near Red, WI
Lower Verm. River	S001-230	Vermillion River at Hwy 68 Bridge, 3/4 Mile norhteast of Etter
Lower Verm. River	VM00.1M	Vermillion River at mouth



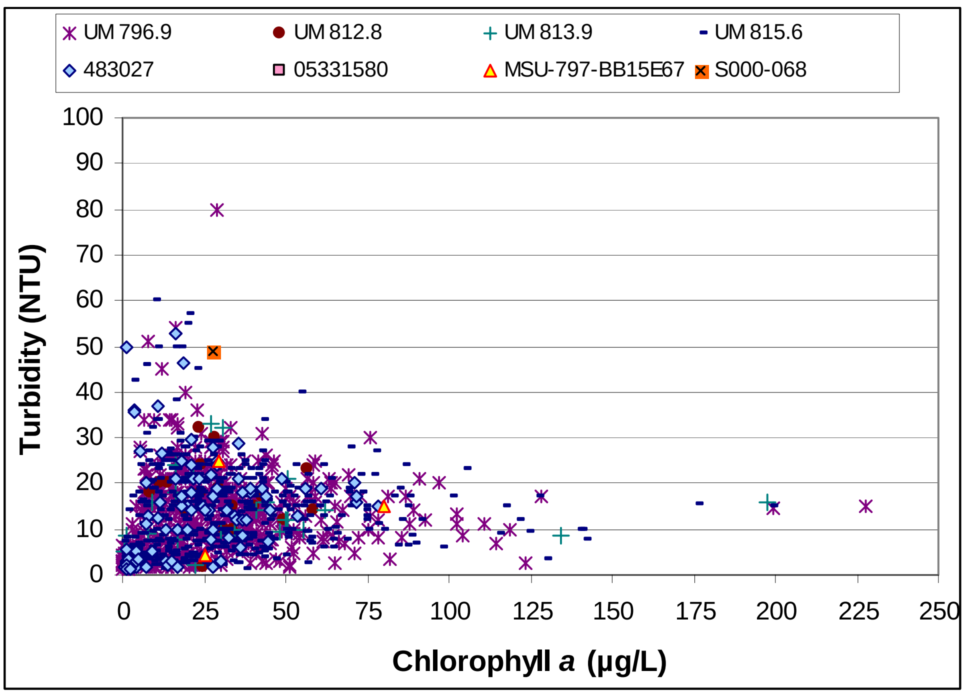
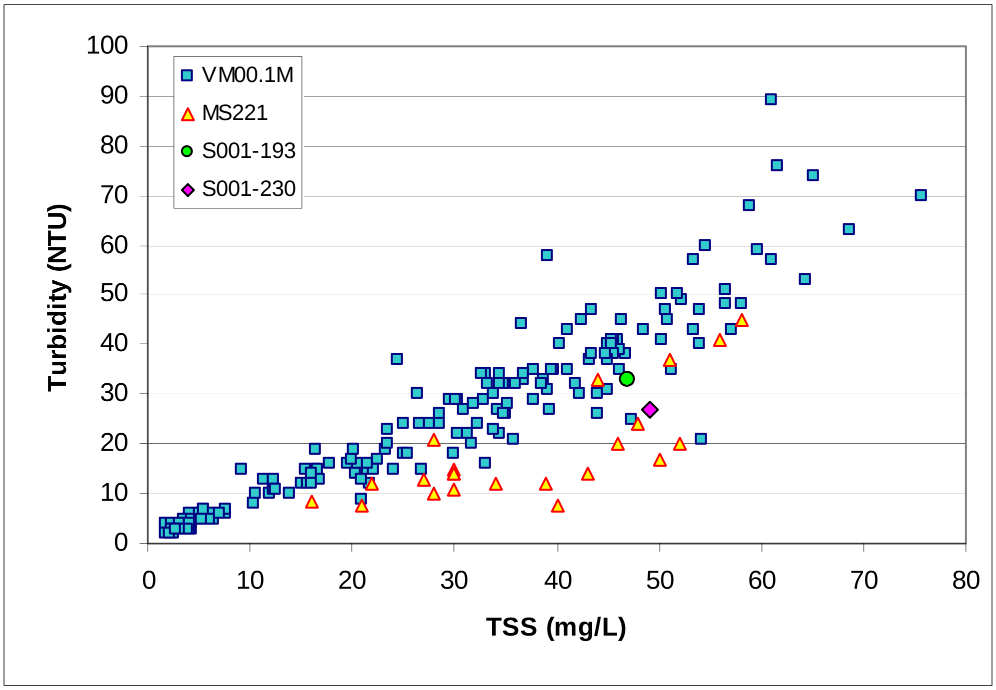


Figure 4-38. Relationship of turbidity with TSS and chlorophyll *a* for Mississippi River Pool 3.



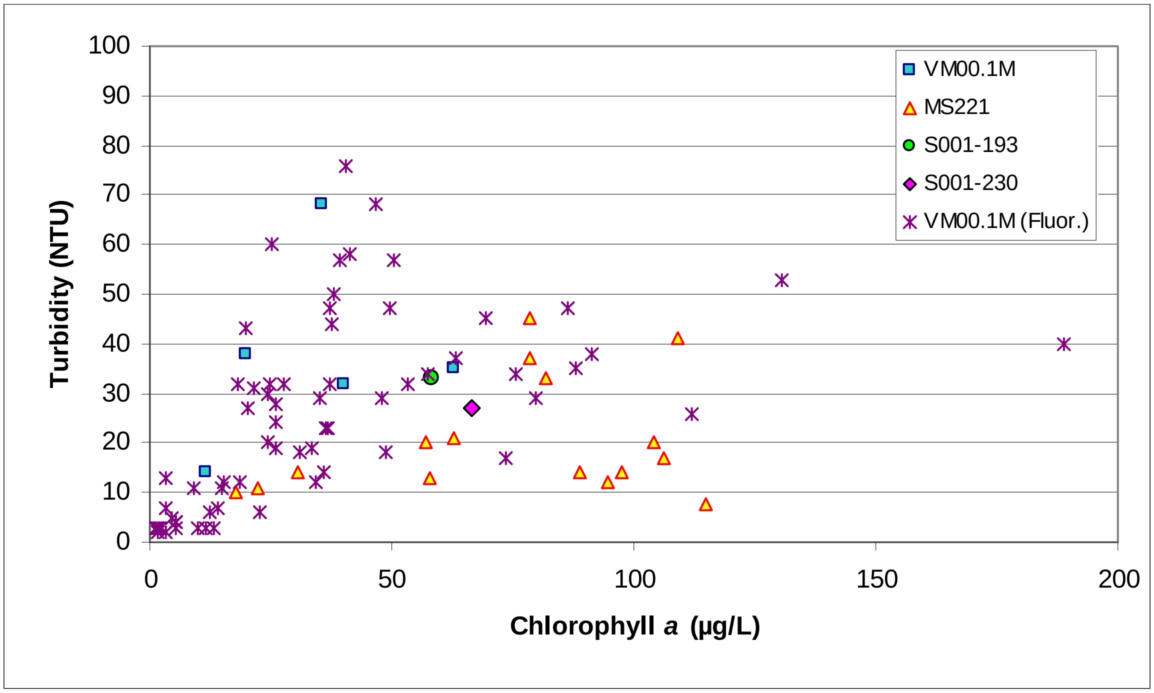


Figure 4-39. Relationship of turbidity with TSS and chlorophyll *a* for LVR.
Note: Chlorophyll *a* by spectrophotometry except for "VM00.1M (Fluor)" results by fluorometry.

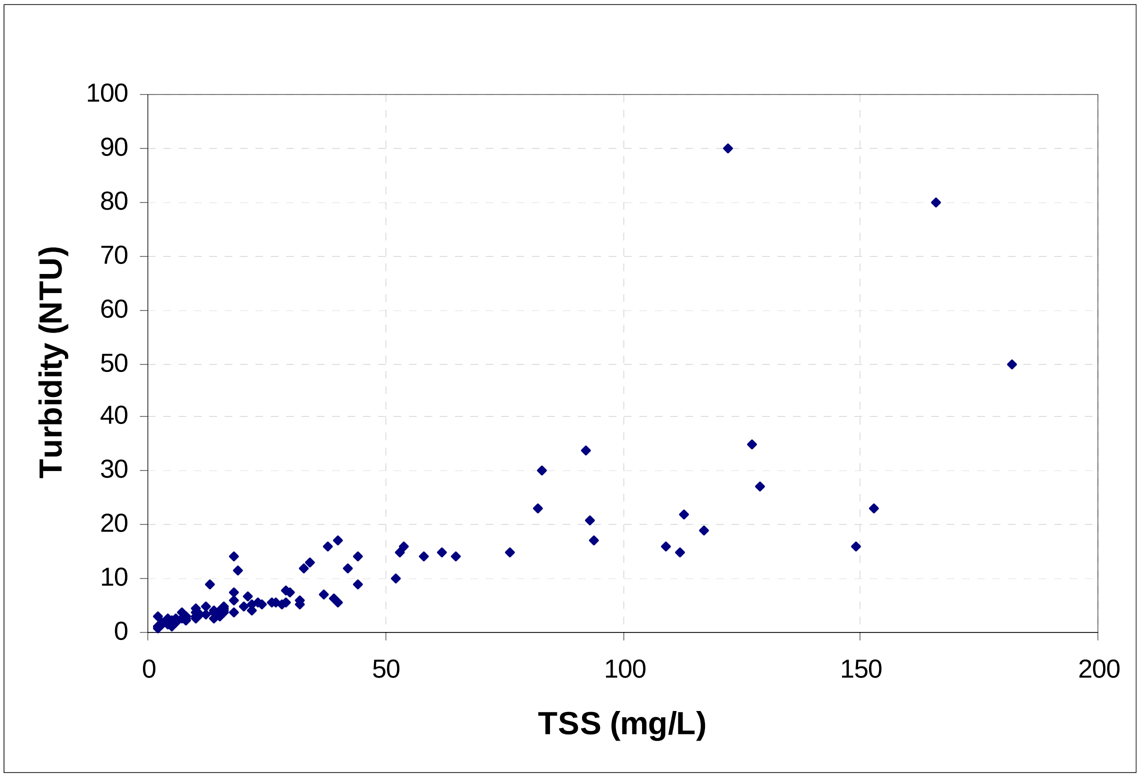


Figure 4-40. Relationship of turbidity with TSS for Upper Vermillion River.

Turbidity samples from two stations, one in Pool 3 (MSU-797-BB15E67) and one in LVR (MS221), were measured using formazin turbidity units (FTUs), which should approximate NTUs (Wilde and Gribs, 1998). Data from both stations were examined to determine whether the turbidity measured using formazin turbidity units were comparable to data collected using nephelometric turbidity units. For station MSU-797-BB15E67, the turbidity-versus-TSS relationship agrees well with that for the other stations, and the limited turbidity versus-chlorophyll *a*-data also agree reasonably with the other stations, so MSU-797-BB15E67 was retained in the subsequent analyses. For station MS221, the turbidity-versus-TSS relationship appears to be different from that station VM00.1M (which has the majority of the data); for a given TSS, turbidity measured at MS221 is consistently lower than that at VM00.1M. The turbidity-versus-chlorophyll *a* relationship follows the same trend. Both stations are in the same area, near the mouth of the Vermillion River. Because of the apparent lack of consistency between turbidity measured at the two stations, MS221 was removed from subsequent analyses. As a result, no analyses using chlorophyll *a* were performed for the LVR, because only seven chlorophyll *a* observations remained after removing MS221.

TSS and chlorophyll *a* are generally correlated with each other because phosphorus loading is correlated with solids loading. This correlation can obscure the relationship between chlorophyll *a* and turbidity. For Mississippi River Pool 3, the correlation coefficient between TSS and chlorophyll *a* is 0.20 (Figure 4-41). The chlorophyll *a*-to-TSS relationship in the Mississippi River appears to be nonlinear. This might reflect high TSS values occurring during high-flow events not conducive to algal growth, the effects of light limitation, or both.

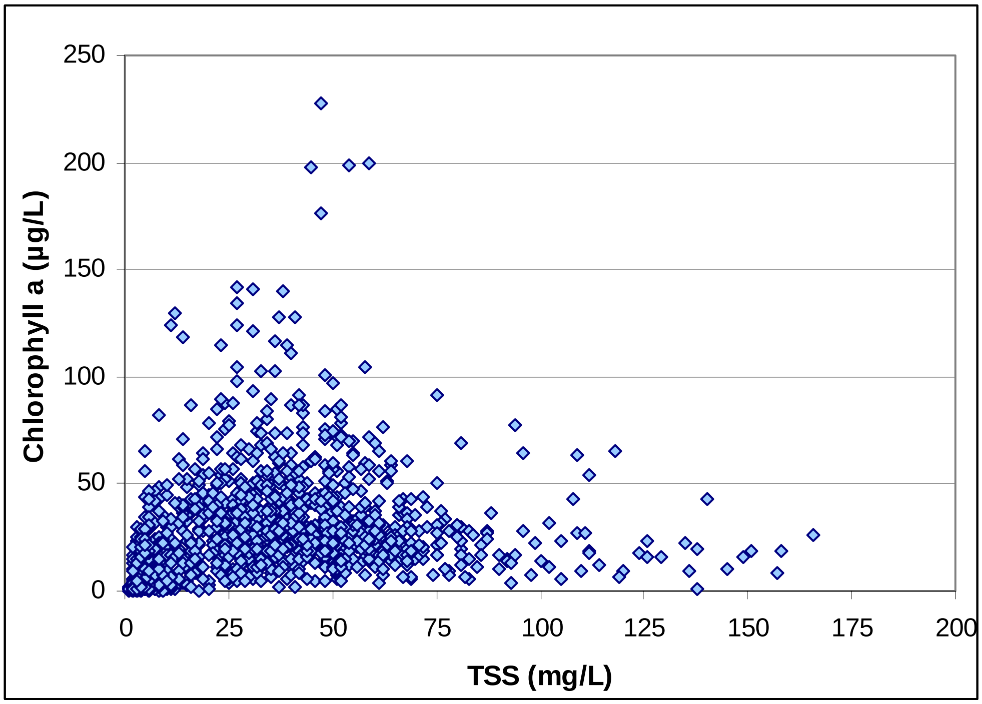


Figure 4-41. Relationship between chlorophyll *a* and TSS for Mississippi River Pool 3.

4.2.1.3 Relationship of Chlorophyll and TVS

As noted above, the TVS component is expected to be associated with algae, although detritus also contributes. Chlorophyll *a* may be a predictor of TVS. Furthermore, the TVS contribution of chlorophyll *a* can be used to evaluate the effects of reduced algal production on turbidity. The ratio is expected to be about 0.1 mg/L of TVS per µg/L chlorophyll *a*.

In Mississippi Pool 3, the relationship is fairly noisy (Figure 4-42). This is likely the result of a more variable detrital load. A regression analysis with all the data provides a relationship with little explanatory power; however, a regression with three high values of removed (shown as red squares) TVS provides a better relationship (R^2 = 53 percent):

$$TVS = 1.633 + 0.0818 \cdot chl\text{-}a.$$

Note that because TNVS and TVS were measured only at stations 483027 and MSU-797-BB15E67, only limited observations are available to develop this relationship in Pool 3.

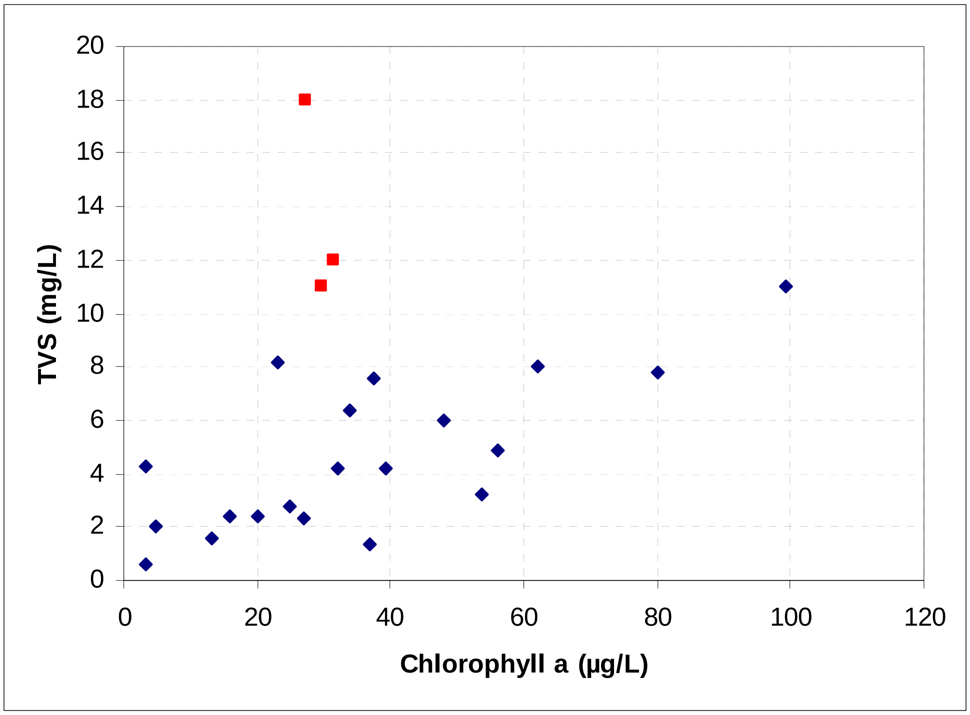


Figure 4-42. Relationship of TVS to chlorophyll *a* for Mississippi Pool 3.

4.2.1.4 Development of TVS Surrogate

The Pool 3 data set includes numerous samples in which chlorophyll is available but TVS is not. Accordingly, a surrogate TVS variable was created for use in regressions. This variable is equal to observed TVS, when available. When chlorophyll *a*, but not TVS, is available, the surrogate is calculated from chlorophyll concentrations, using the regressions for Pool 3. If the surrogate TVS is greater than the observed TSS, then the surrogate TVS is set equal to TSS because TVS cannot be greater than TSS. NVS is equal to TSS minus observed or estimated TVS.

4.2.1.5 Regression Analysis for Turbidity

A variety of linear and nonlinear regressions for the prediction of turbidity were developed. These are summarized in Table 4-11 and Table 4-12. Because both linear and nonlinear models are involved, the unadjusted R^2 is reported as a basis for comparison of fit. In most cases, for models in the form of Equation 2 or Equation 3 the β_1 parameter was not significantly different from zero and is omitted. For Pool 3, the best-fit model was a nonlinear fit on TSS and chlorophyll *a*; for the Lower Vermillion, the best-fit model was a nonlinear fit on NVS and TVS. For the Upper Vermillion, only TSS is available as an independent variable, and the best fit is the nonlinear model. The intercept term is not significantly different from zero in Pool 3 or the LVR, suggesting that dissolved organic color is not a significant contributor to turbidity independent of TSS.

There is, however, only a small difference between the fit of the different model forms, suggesting there is little advantage in going to the more complex models for which fewer data are available. Therefore, the best predictor of turbidity is judged to be models of the form

$$Turbidity = \beta_0 + TSS^{\alpha}.$$

The more complex relationships to TVS or directly to chlorophyll *a* are, however, useful for post-analysis of the fractional contribution of algae to the total turbidity in the system.

Table 4-11. Regression Models for Prediction of Turbidity (NTU) Based on TSS (mg/L), TVS (mg/L), NVS (mg/L), and/or Chlorophyll *a* (μg/L)

Model	n	R^2	β_0	β_1	α	γ
Lower Vermillion River						
Turbidity = β_0 + NVS^{α} + γ TVS	183	95.81	-1.768	-	0.941	1.216
(*) Turbidity = β_0 + TSS^{α}	186	95.67	-1.098	-	0.974	-
Turbidity = β_0 + β_1 TSS	186	87.22	-0.487	0.889	-	-
Mississippi Pool 3						
Turbidity = β_0 + β_1 NVS^{α} + γ TVS	1265	76.34	1.719	1.019	0.733	-0.0677
Turbidity = β_0 + NVS^{α} + γ TVS	1265	76.34	1.752	-	0.737	-0.0635
Turbidity = β_0 + TSS^{α} + γ chl-a	1265	76.45	0.689	-	0.745	-0.0309
(*) Turbidity =β_0 + TSS^{α}	1366	75.26	0.0449	-	0.741	-
Turbidity = β_0 + β_1 TSS	1366	74.00	2.865	0.293	-	-
Turbidity = β_0 + β_1 TSS + γ chl-a	1265	74.56	3.106	0.294	-	-0.0109
Upper Vermillion River						
(*) Turbidity = β_0 + TSS^{α}	101	74.94	-2.71	-	0.739	-
Turbidity = β_0 + β_1 TSS	101	63.86	0.443	0.264		

(*) Recommended predictive model.

Table 4-12. P-values for Coefficients in Recommended Models

	β_0	α
Lower Vermillion River	0.16	< 0.01
Mississippi River Pool 3	0.81	< 0.01
Upper Vermillion River	0.02	< 0.01

Observed-versus-predicted turbidity values, using the recommended predictive models, are shown for Pool 3 and the LVR in Figure 4-43 and Figure 4-44. The relatively poorer fit for the LVR might reflect a more heterogeneous makeup of TSS in this system.

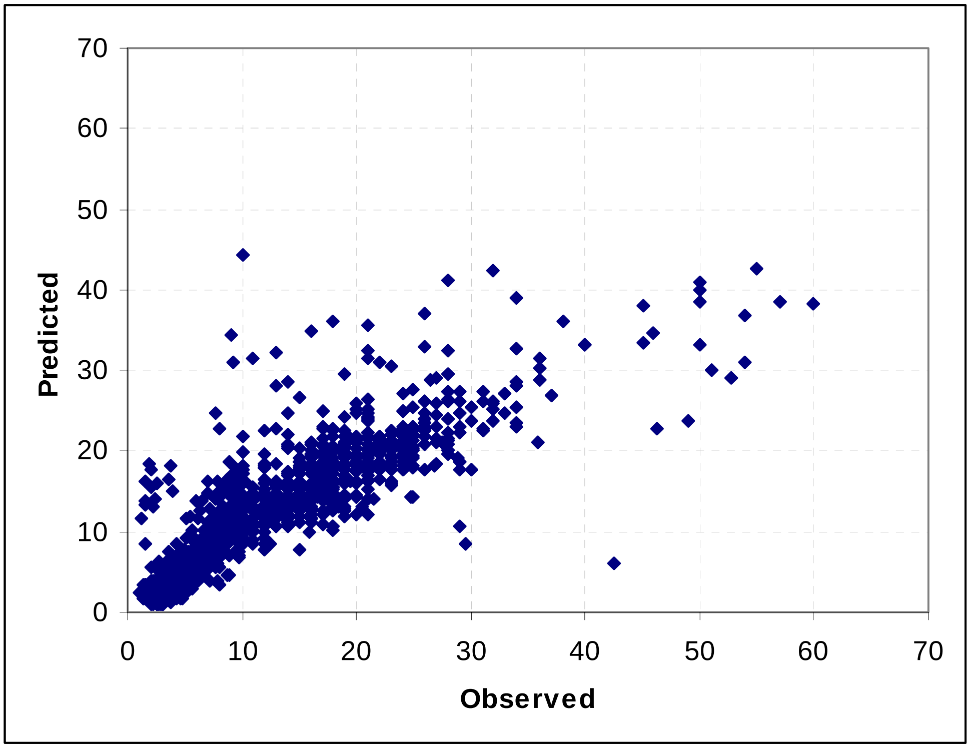


Figure 4-43. Predicted vs. observed turbidity (NTU) for Mississippi Pool 3.

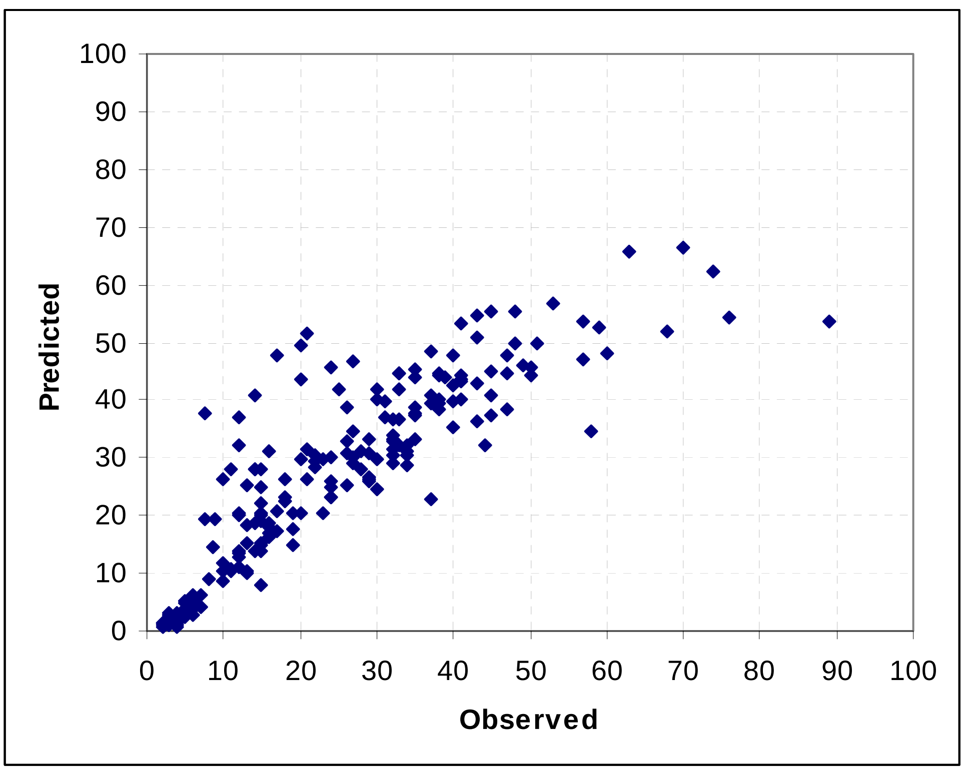


Figure 4-44. Predicted vs. observed turbidity (NTU) for Lower Vermillion River.

4.2.1.6 Discussion of Results for Turbidity

Recently, the Upper Mississippi River Conservation Committee developed proposed light-related water quality criteria to sustain submersed aquatic vegetation (UMRCC, 2003). This work is based on light availability, and the primary recommendation is to maintain a growing season average vertical light extinction coefficient of 3.42 per meter or less. However, secondary recommendations were also developed for Secchi disk depth (greater than 0.5 meter), TSS (less than 25 mg/L), and turbidity (less than 20 NTU). To develop the translation factors, the UMRCC developed a series of regression equations based on large sets of data obtained in Mississippi River pools 8, 9, and 13.

Combining the relationships developed by UMRCC for light extinction yields the relationship

$$\boldsymbol{Turbidity = 1.78 \cdot TSS^{0.746}.}$$

The regression model developed in this section for Mississippi River Pool 3 has a similar exponent but a multiplicative coefficient of 1, and thus it yields lower turbidity values for a given concentration of TSS. For instance, at 25 mg/L TSS, the UMRCC relationships predict 19.6 NTU whereas the Pool 3 regression presented above yields 10.9 NTU. Within Pool 3, TSS concentrations of 25 mg/L correspond to turbidity primarily in the range of 5 to 15 NTU, with only a very few values as high as 15 NTU, as shown in Figure 1. In part, this difference might reflect changes in sediment quality in the lower pools, where finer clays that produce more light scattering per unit weight might be more important. The comparison to the UMRCC results is not fully valid, however, because the UMRCC regressions force the relationships to light extinction through zero, which distorts the relationship between TSS and turbidity. Furthermore, the relationship between light extinction in TSS in the UMRCC data has a large amount of scatter and the re-derived multiplicative coefficient presented above results from the division of two uncertain numbers.

The models presented above based on NVS and TVS concentrations provide slightly better fits to turbidity compared to the simple nonlinear model on TSS, in both the LVR and Mississippi Pool 3, but they are of less practical use because the volatile solids fraction is not always reported. These equations do, however, provide a basis for speculation as to the relative importance of inorganic and organic solids to turbidity in the system.

For the LVR, the mean concentration of NVS is 21.5 mg/L, while that of TVS is 8.2 mg/L, yielding a predicted average turbidity of 26.2 NTU. Of this amount, 62 percent (16.2 NTU) appears to be due to non-algal sources. For Mississippi Pool 3, the coefficient on TVS is slightly less than zero, suggesting that observed turbidity is almost entirely due to inorganic sediment.

As noted above, the TVS concentration is expected to drop by about 1 mg/L for each 10 µg/L drop in chlorophyll *a*. The estimated coefficient on TVS for the turbidity equation is close to 1.2, suggesting that a reduction of 20 µg/L in chlorophyll *a* would only reduce turbidity by only 2.4 NTU. Negative coefficients on chlorophyll *a* on regressions of turbidity against TSS and chlorophyll also suggest that algae do not play the major role in the observed turbidity. Algal concentration, however, is likely to have a much greater impact on light penetration (e.g., Secchi depth) than on light scattering (turbidity).

These findings suggest that nephelometric turbidity problems in the LVR are largely sediment-driven, consistent with the analysis done for the Goose Lake study (UMRSEMP, 1990). If so, only a small improvement in observed turbidity can be expected to result from phosphorus reductions that reduce algal growth.

4.2.2 LVR Turbidity Conceptual Model

Turbidity in the water column results from a combination of inorganic sediment, living algae, organic detritus, and color associated with dissolved organic compounds. The local watershed of the LVR, the LVR channel, the Upper Vermillion River, and Mississippi Pool 3 might all be sources of loads of sediment and organic material that contribute to turbidity. In addition, phosphorus loads are important because they may promote algal growth in the LVR. A general conceptual framework for turbidity in the LVR is shown in Figure 4-45. The figure connects stressor sources (at the bottom) with the management target, turbidity, at the top. Each individual pathway (bottom to top) through the diagram can be considered a risk hypothesis for elevated turbidity.

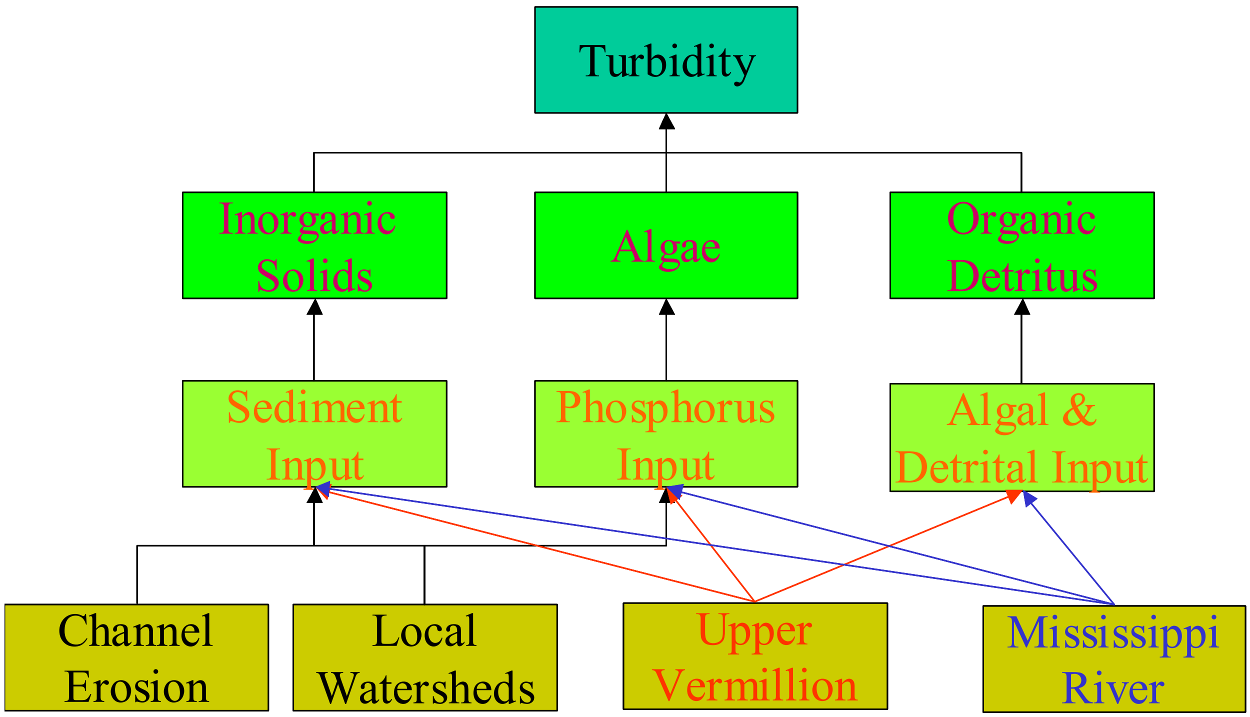


Figure 4-45. General conceptual model of turbidity in the LVR.

All the pathways through this diagram are of potential importance; however, some are clearly more important than others. From the discussions in the preceding sections, the following tentative inferences can be made:

- Inorganic sediment appears to be the primary cause of elevated turbidity (Section 4.2.1.6). This suggests that the risk pathways through the box "Sediment Input" in Figure 4-45 are the most important.

- Pathways involving algae and organic detritus are generally of lesser significance to turbidity in the LVR, but they do provide a contribution (about 38 percent of turbidity on average arises from all volatile solids).

- Volatile solids (algae and organic detritus) do not appear to be a significant component of turbidity in Mississippi Pool 3. External loads of algae and detritus to the LVR are likely not significant contributors to the turbidity problem.

- Algal growth within the LVR is a secondary, although not the major, contributor to turbidity. Therefore, an analysis of phosphorus input to the system will be useful.

Based on these findings, the primary need for evaluation of the turbidity conceptual model is creation of a conceptual model for sediment. This is addressed in Section 4.3. A secondary need is the creation of a conceptual model for nutrients and algae. This is addressed in Section 4.4.

4.3 LVR Suspended Sediment

4.3.1 Sediment Loading from the Upper Vermillion River

MCES has provided continuous flow monitoring of the Vermillion River at Hastings since 1994. MCES also has reported 144 usable individual-day TSS results since 1995. Many of these are composite overflow events, but MCES has also calculated and reported corresponding composite flows.

The current plan of work for the LVR assumes that loads from the Upper Vermillion River can be estimated from monitoring. There is no provision for creating of a watershed model. This approach would require filling in the time series of solids loads. In many cases, this can be accomplished by developing a rating curve. This section of the report summarizes the sediment data and resulting rating curve. The predictive power of the approach is low for the Vermillion, which will introduce uncertainty into simulation of the solids balance in the LVR.

4.3.1.1 Sediment Rating Curve

MCES reports composite samples of TSS and corresponding flow at gage 213567 for April 1995 through November 2003. The gage is inside the ConAgra Mill at 2005 Vermillion Street near Highway 61 in Hastings. TSS concentrations range from 2 to 214 mg/L, with an average of 48 mg/L.

A sediment rating curve typically relates suspended sediment concentration to discharge. A plot of all TSS data versus flow shows only weak correlation between the two measures (Figure 4-46). Indeed, some of the highest concentrations occur at low-flows, while low concentrations occur at high flows.

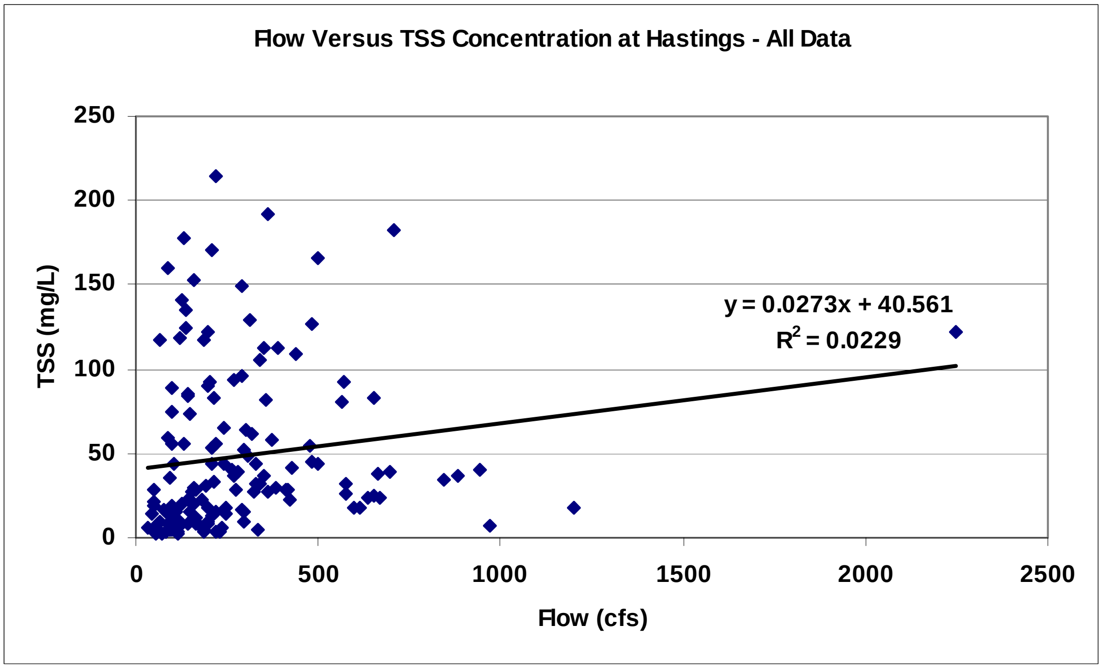


Figure 4-46. TSS vs. flow in MCES monitoring at Hastings.

Some of the noise in the relationship might be due to seasonal variability. Plotting the results by season, however, does little to resolve the relationship (Figure 4-47). Note that few samples are available for the winter period.

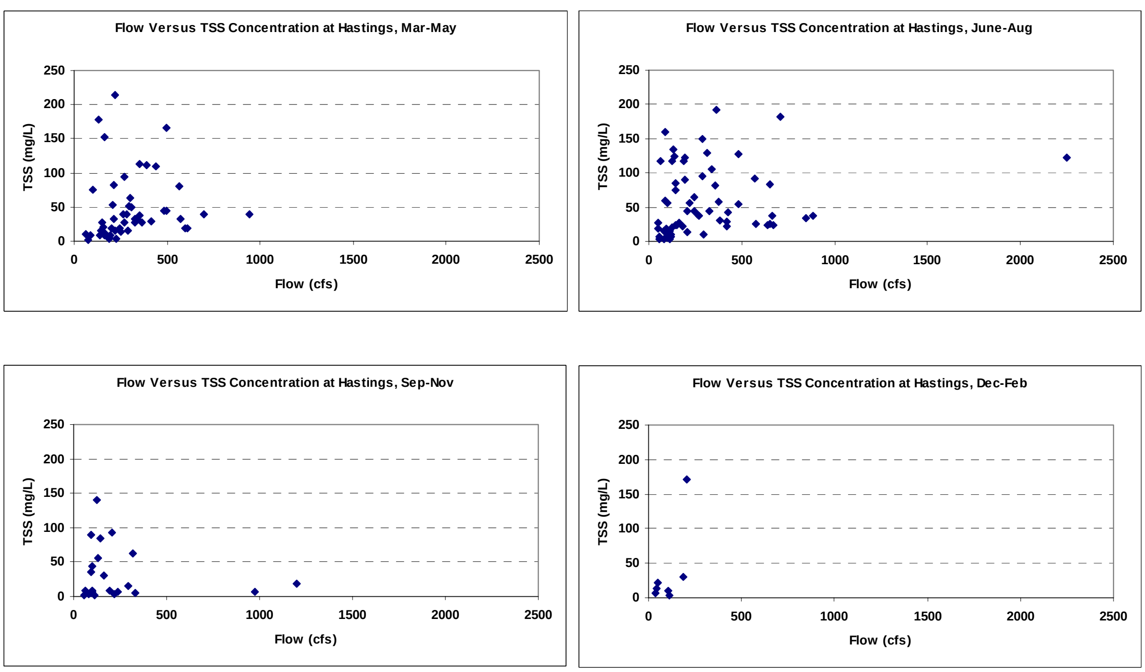


Figure 4-47. TSS vs. flow at Hastings by season.

4.3.1.2 Sediment Power Curve

TSS concentration at Hastings is not well predicted by flow. A sediment load power curve, plotting log load versus log flow, of necessity provides a stronger relationship because as load is a linear function of flow.

Estimated suspended sediment loads at Hastings range from 0.3 to 740 tons/day, with an average of 42 tons/day. The power curve relationship is shown in Figure 4-48, with load expressed in pounds per day.

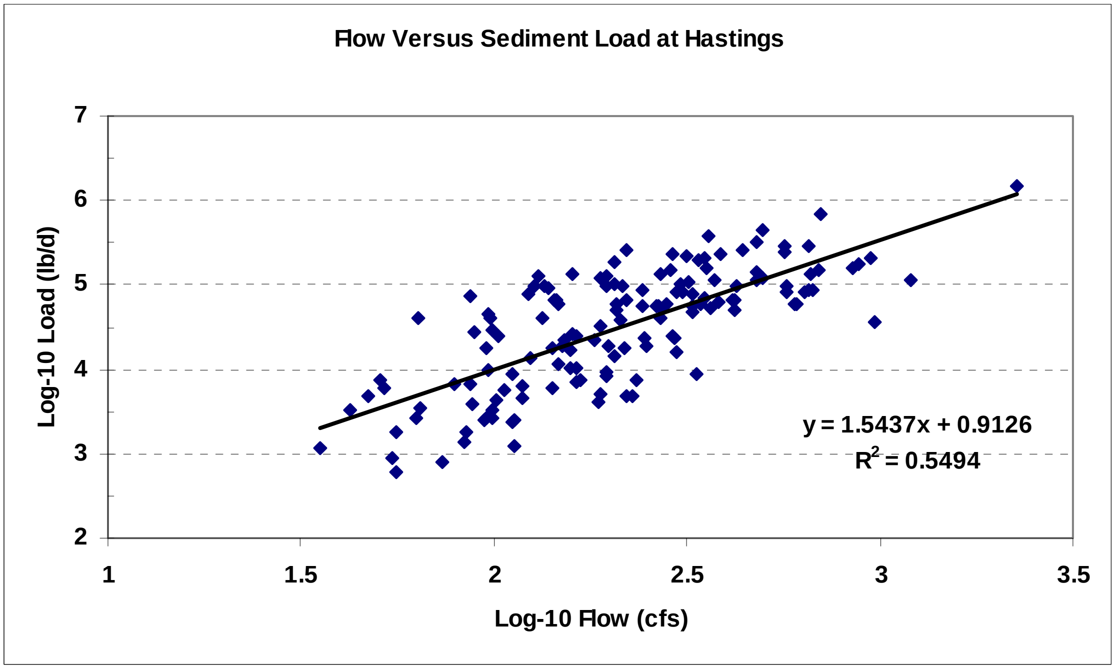


Figure 4-48. Sediment load power curve for MCES gage 213567, Vermillion River at Hastings.

4.3.1.3 Load Estimation

Preston et al. (1991) investigated the performance of 24 different methods proposed for estimating mass loads in streams from limited concentration observations. These methods include various types of averaging, ratio, and regression estimators, applied with and without stratification and under systematic and event-focused sampling, with evaluation of error and bias. Preston et al. concluded that no single estimator could be determined *a priori* superior for a given situation. Certain estimators, however, performed relatively well for all test situations. In particular, ratio estimators (adapted from sampling statistics) were recommended as robust to sources of bias inherent in flow-concentration relationships and, when stratified by flow, were also resistant to bias in event sampling. Ratio estimators are particularly appropriate when the relationship between flow and concentration is weak.

The ratio estimator of Cochran (1977), calculated over k individual strata, is:

$$\hat{L} = \sum_{h=1}^{k} \left({l_h}/{q_h} \right) Q_h$$

where L is the total annual estimate of load, l_h is the average load on days when measurements were taken in the stratum, q_h is the average flow on days when measurements were taken in the stratum, and Q is the sum of all daily flows falling within that stratum over the course of the year. The estimated load on an individual day is simply the product of a flow-weighted mean concentration within the stratum times observed flow.

The USACE's FLUX program (Walker, 1987) implements a variety of these estimation methods, including the ratio estimator (referred to as "flow-weighted concentration"). Application of the FLUX model shows that an approximate minimum of the coefficient of variation (CV) of load estimates is obtained with flow stratification at 90 hm^3/yr (100 cfs) and 275 hm^3/yr (309 cfs). With this stratification scheme, the estimated CV for the ratio method is 0.088. This is slightly superior to the CVs produced by other methods, including the regression methods, and has the further advantage of being asymptotically unbiased, unlike the regression methods.

FLUX has been used to calculate a daily series of estimated TSS loads (in kilograms), using the ratio method, for 1994 through 2002; 2003 has not been estimated because the full flow series for this year has not yet been provided. FLUX provides two types of load estimates interpolated and uninterpolated. The uninterpolated loads are those produced directly by the ratio estimator, and they have constant concentrations within a stratum. The interpolated estimates are adjusted by interpolating residuals between sampling dates up to a user-specified maximum time separation. The time window for these estimates is set at 14 days. The interpolated estimates are useful to account for serial correlation. They also aid in adjusting the time series to reflect temporal changes in the relationship between TSS and flow. Interpolated daily load estimates are shown in 0. Over the 9 years of simulation, the TSS load at Hastings has averaged 5,572,809 kg/yr at a flow-weighted average concentration of 41 mg/L. Given an upstream watershed area of 277.98 mi^2, this translates to a *delivered* sediment yield of 77 kg/ha or 69 lb/ac/yr.

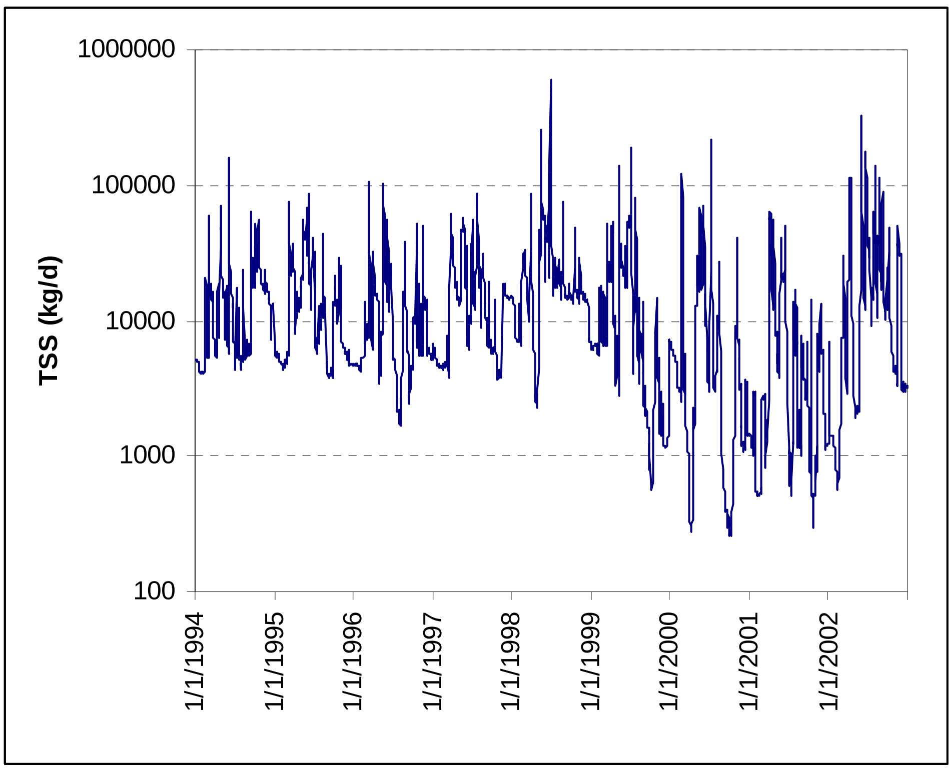


Figure 4-49. Estimates of daily TSS load in the Vermillion River at Hastings. Calculated from MCES data using ratio method in FLUX with 14-day interpolation window on residuals.

4.3.2 Sediment Delivery from Tributaries to the LVR

As noted in Section 4.1.4, local direct tributaries to the LVR contribute an additional 28 percent of drainage area to the area of the watershed at the MCES gage in Hastings. In addition to flow, these tributaries also contribute sediment load. The mass contribution might be considerable, given that the delivered yield at Hastings is 22 tons/mi^2/yr and the smaller tributaries are likely to have a higher delivery ratio. In addition, the steep topography associated with the Mississippi bluffs can lead to high erosion potential. To date, an analysis of sediment loading from LVR tributaries has been identified for only Etter Creek.

4.3.2.1 Etter Creek

Since the late 1970s, the Soil Conservation Service (now the Natural Resources Conservation Service) of the U.S. Department of Agriculture has assessed erosion and sedimentation in the Etter Creek watershed. In *Inventory and Evaluation of Natural Resources and Related Problems in the Etter Creek Watershed (SCS, 1978)*, the SCS identified the primary regions of soil loss in the watershed and suggested methods of erosion control that were specific to soil type and land use. The report focused on streambank erosion and poor farming practices as the two main sources of sediment loading to the creek.

To control streambank erosion, the SCS suggested that a floodplain be constructed for the lower sections of Etter Creek and that this floodplain be connected to the floodplain of the Vermillion River. Installation of grade control structures and water impoundment structures was also recommended.

The primary land use in the Etter Creek watershed at the time of the SCS inventory (and to this day) was row crop farming. Most of the farming practices identified in the 1978 report involved up-and-downhill tillage with no erosion control. Combining moderate slopes in the watershed with poor farming practices results in high peak flows from cropland. Not only do these flows contribute to streambank erosion in Etter Creek, but they also carry large volumes of eroded soil.

In 2002 the Dakota County Soil and Water Conservation District (SWCD) began a watershed assessment of Etter Creek with the intention of developing a streambank restoration plan for one of the severely eroded banks. The Dakota County SWCD teamed with the National Park Service (NPS) and the Association of Metropolitan Soil and Water Conservation Districts (MASWCD) to identify the major sources of sediment and the areas of highest erosion and to assess overall channel morphology (Dakota County SWCD, 2002). During this assessment, the team identified the section of Etter Creek just downstream of three large culverts under Red Wing Boulevard as the most severely eroded segment of the creek. Bank height along this segment was 50 feet, and plans for restoration were outlined in the report.

The final project report (Dakota County SWCD, 2003) stated that restoration of the streambank below Red Wing Boulevard was completed in the fall of 2003 by realigning and lengthening the channel. The new channel was positioned 50 feet from the original streambank. Impacts of the restoration had not been assessed at the time of the report.

Though poor farming practices were identified as a primary source of sediment in both the 1978 and 2002 assessments, no implementation plans were put in place to improve cropland management. In the 1978 report, the SCS did suggest contour tillage and erosion control structures, but the recommendations were rarely fulfilled. The 2002 report does not address the problem except to say that the hydrologist from the National Park Service recommended “improving agricultural practices immediately, with the long-range goal of converting the landuse practices entirely from row crops to pastures, tree farms, and wood lots.”

4.3.3 Loading from Mississippi River Pool 3: Comparison to Upper Vermillion

A comparison of concentrations in the Upper Vermillion at Hastings and Mississippi Pool 3 is useful to determine which source of flow to the Lower Vermillion tends to dilute the other. All available stations within Pool 3 were pooled for this analysis.

For TSS, there are concurrent recent data from 1995 on, shown in Figure 4-50. Although there is more variability in the Upper Vermillion data, concentrations in the two systems are generally in the same range. Box and whisker plots by season (Figure 4-51) do not reveal any consistent differentiation between the two systems. Summary statistics (Table 4-13) show that the Upper Vermillion has a higher mean concentration but Mississippi Pool 3 has a higher median concentration. Because TSS concentration has a weak positive correlation with flow in the Upper Vermillion, this suggests that the Upper Vermillion might contribute a greater load per unit of inflow during storm events, while the Mississippi may contribute a greater sediment load per unit of inflow during moderate flows..

In sum, periods in which the water source in the LVR shifts from Upper Vermillion River to Mississippi Pool 3 inflow tend to produce little change in TSS input concentration, but loading per unit of inflow might be greater for the Upper Vermillion. However, large flows in the distributaries from the Mississippi could also enhance the solids load through channel erosion in the unstable floodplain soils of the LVR.

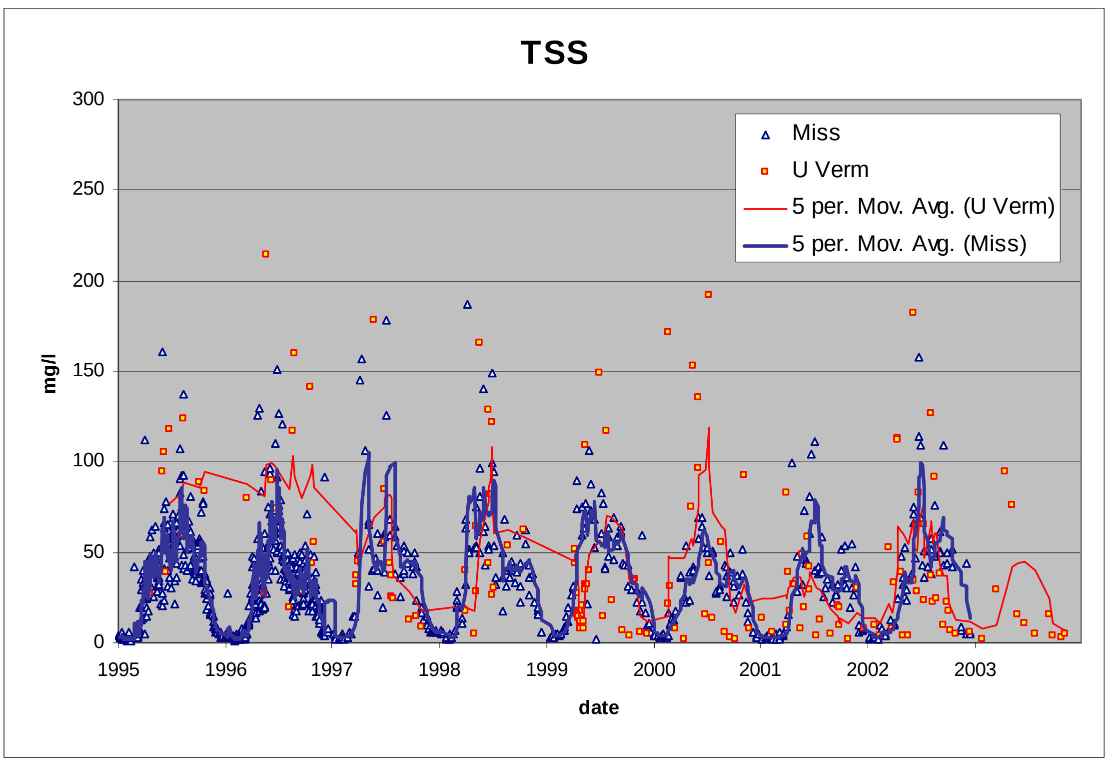
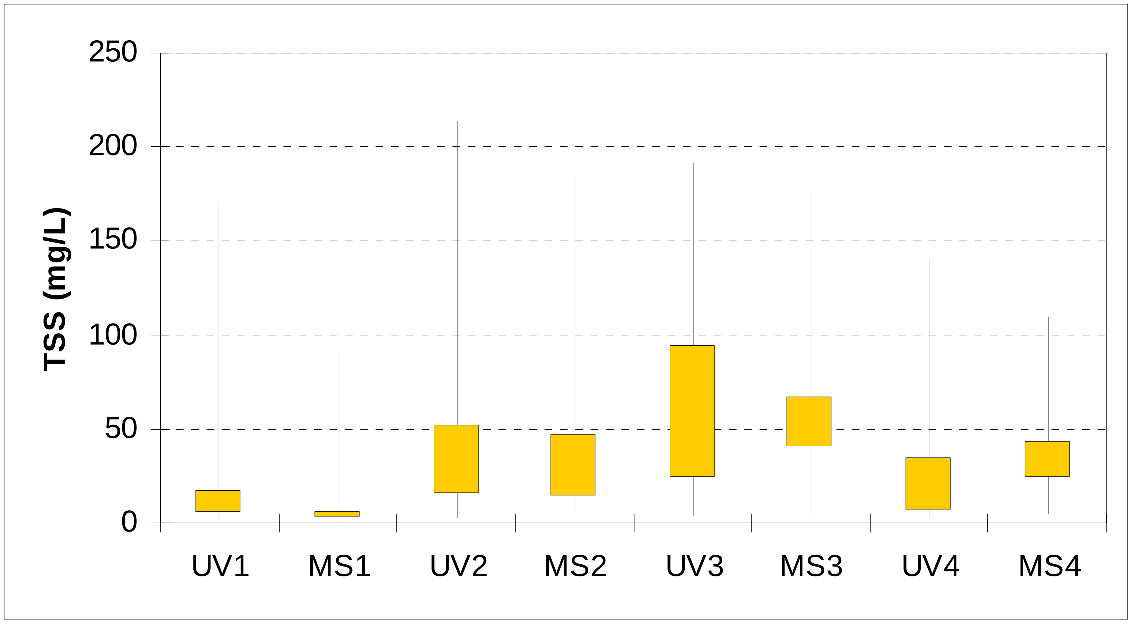


Figure 4-50. Comparison of TSS concentrations in the Upper Vermillion River at Hastings and Mississippi River Pool 3.



Notes: UV = Upper Vermillion
MS = Mississippi Pool 3.
1 = Dec–Feb, 2 = Mar–May, 3 = June–Aug, 4 = Sep–Nov
Central boxes show the interquartile range (25th to 75th percentile).
Whiskers extend from minimum to maximum observed value.

Figure 4-51. Seasonal box and whisker comparison of TSS concentrations in the Upper Vermillion River at Hastings and Mississippi River Pool 3.

Table 4-13. TSS Statistics for Mississippi Pool 3 and Upper Vermillion River, 1995–2003

	Mean	Median
Mississippi Pool 3	34.3	32
Upper Vermillion River	46.5	29

4.3.4 Internal Sources from Channel Erosion and Resuspension

The LVR flows in the floodplain of the Mississippi River, which consists of large, primarily unconsolidated deposits of glacial and fluvial origin. These deposits are readily eroded, although the erosion potential is reduced by the low gradient of the system. Examination of topographic maps and compilation of historical information (Section 2) reveal that the channel of the LVR and the interconnections with the Mississippi have meandered and switched course frequently over time. The system is thus actively reworking its floodplain sediments, suggesting a significant potential for internal mobilization of channel sediment.

The primary impetus for channel erosion in the LVR appears to be the large inflows that occur sporadically from the Mississippi River. Anecdotal evidence suggests that log jams and ice jams might play an important role in promoting channel movement.

No information is available with which to estimate the magnitude of this sediment source at this time. Conceptually, however, channel scour erosion occurs in significant amounts only under high-flow conditions and is less important under normal-flow conditions.

A more important consideration for summer turbidity in the lower portions of the LVR might be wind-induced resuspension of fine sediments in the LVR lakes. A study of Goose Lake (UMRSEMP, 1990), connected tangentially to the LVR, characterized the bottom substrate as consisting of unstable, fine material without submersed aquatic vegetation. Wind-induced turbulent resuspension was considered to be a major factor in elevated turbidity in Goose Lake. The other lakes in the system that provide sufficient open fetch to develop wind-induced waves could also be important sources of turbidity to the LVR. Quantitative data to evaluate the importance of this source are not, however, available at this time.

4.3.5 Conceptual Model for Sediment in the LVR

Although a complete sediment budget cannot be estimated for the LVR at this time, scoping-level estimates can be provided (Table 4-14). The following assumptions are made:

- Load from the Upper Vermillion River is represented by the FLUX results, averaging 6,143 t/yr.
- Load from Mississippi Pool 3 can be estimated as the ratio of flow from Pool 3 into the LVR to flow from the Upper Vermillion River (Section 4.1.6.1), times the ratio of mean TSS concentrations in the two sources (34.3/46.5).
- Load from local tributaries can be roughly approximated by using the per-acre sediment yield for the Upper Vermillion River and correcting for the higher delivery expected for smaller tributaries. Assuming the effective watershed size is on the order of 8 mi^2 for the local tributaries versus 278 mi^2 for the Upper Vermillion at Hastings, the increase in delivery ratio should increase the yield per acre by a factor of about 3, using the delivery ratio diagram in Vanoni (1975).
- Load from channel erosion is not known at this time. Over the long-term, erosion and deposition within the LVR are likely to balance out; however, channel erosion might be an important source of increased suspended sediment and turbidity during high-flow events.

Table 4-14. Scoping Level Estimate of Sediment Inputs to the LVR

Source	Average Load (tons per year)	Percentage
Upper Vermillion River	6,143	21
Mississippi Pool 3	18,354	62
Local tributaries	5,175	17
Channel erosion	?	?
Total	29,672	

Note: Total and percentages were calculated without channel erosion, which is not quantified at this time.

4.4 LVR Nutrients and Algae

As described in Section 3.4, chlorophyll *a* concentrations in the LVR are highly variable, but they often reach the high concentrations (greater than 40 µg/L) typical of algal bloom conditions. Algal blooms limit light and increase turbidity, and thus algae must be part of the turbidity analysis. Algae, however, appear to be a minor component of the total turbidity in the LVR; with most of the turbidity is attributable to inorganic solids (Section 4.2.1).

4.4.1 Nutrient-Algal Relationships

Growth of algae requires nutrients (principally nitrogen and phosphorus) and light. A shortage of any of these components reduces algal growth. In addition, high flows can deplete algae in a flowing river through washout. Many parts of the LVR, other than the lake areas, have a hardwood canopy that limits light availability. Light is further limited by turbidity, and high flows from the Mississippi can flush algae out of the system. As a result, observed chlorophyll *a* concentrations in the LVR are highly variable and do not show a direct and obvious relationship to nutrient concentrations.

Excess algal growth in freshwater systems is most often controlled by limiting phosphorus concentrations. A general guideline based on the stoichiometry of algal cells is that nitrogen-to-phosphorus (N:P) ratios of greater than about 15 indicate that phosphorus is the nutrient most limiting on algal growth, while an N:P ratio of less than 10 indicates that nitrogen is the nutrient most limiting on algal growth. An examination of the N:P ratio for samples from the LVR (Figure 4-52) indicates that the ratio is predominantly greater than 10 and mostly greater than 15. Therefore, phosphorus should be at least potentially limiting on algal growth.

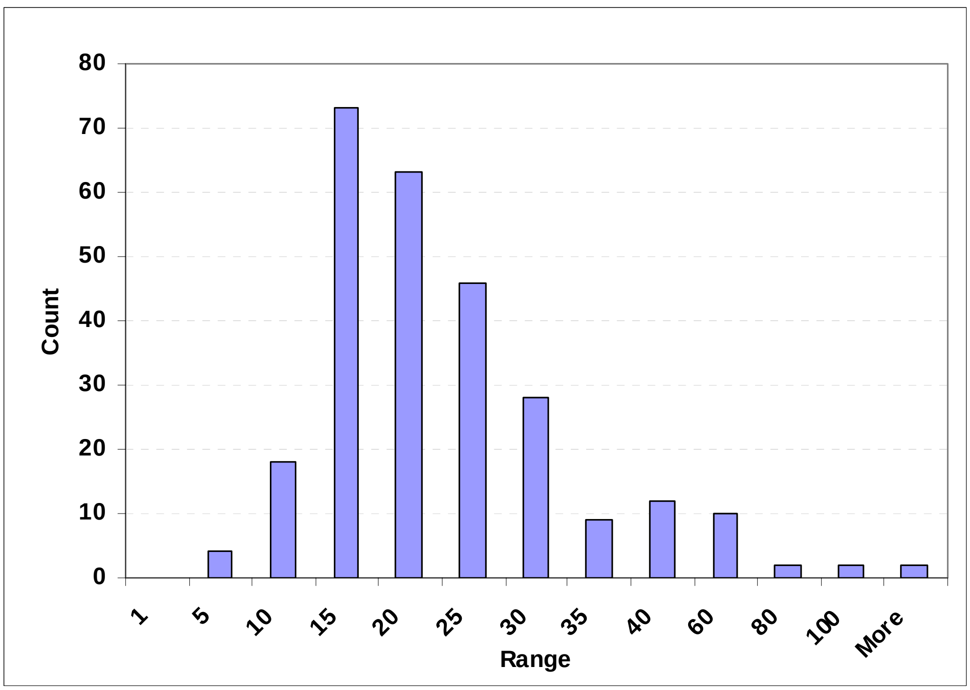


Figure 4-52. Frequency distribution of nitrogen-to-Phosphorus Ratios in the LVR.

Although phosphorus might be the limiting nutrient, a plot of chlorophyll *a* concentration versus total phosphorus concentration in all LVR stations shows little if any clear relationship (Figure 4-53).

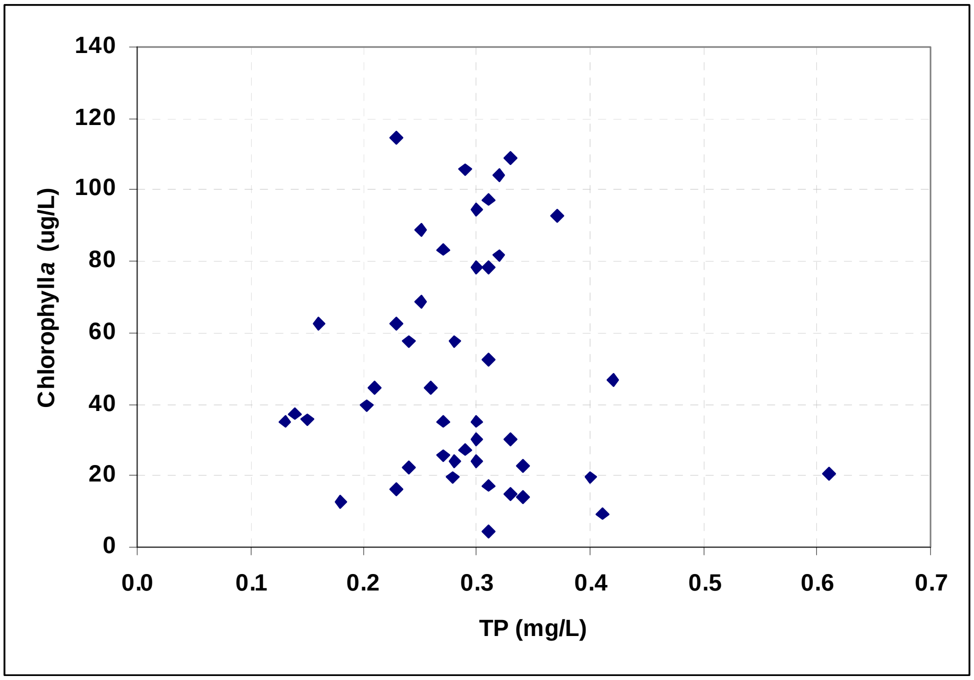


Figure 4-53. Relationship of chlorophyll *a* to total phosphorus concentration in the LVR.
Note: Plot shows spectrophotometric chlorophyll *a* data from stations MS 297, MS 299, MS 221, and VM 00.1M

The large degree of scatter shown in this figure largely reflects the influence of other limiting factors, such as light limitation and advection out of the system. A second factor is that the total phosphorus concentration is generally high and often presents at amounts in excess of algal growth needs. For instance, simulations of the Minnesota River predicted that algae would not respond to phosphorus reductions until the total phosphorus concentration dropped below about 0.22 mg/L, while concentrations above 40 µg/L could still be supported by total phosphorus concentrations of 0.1 mg/L— lower than any measured in the LVR.

It thus appears that algal growth in the LVR is most strongly limited by factors other than nutrients, including light availability. Nevertheless, phosphorus in the system should still be evaluated because of its potential to limit algal growth.

4.4.2 Phosphorus Loading from the Upper Vermillion River

An excellent record of total phosphorus concentration measurements from 1995 through 2003 is available from MCES monitoring at Hastings. Concentrations at this gage show an inverse relationship to flow (Figure 4-54). This reflects the fact that the Empire WWTP is a major source of phosphorus in the system, releasing a fairly constant load that is progressively diluted by higher flows.

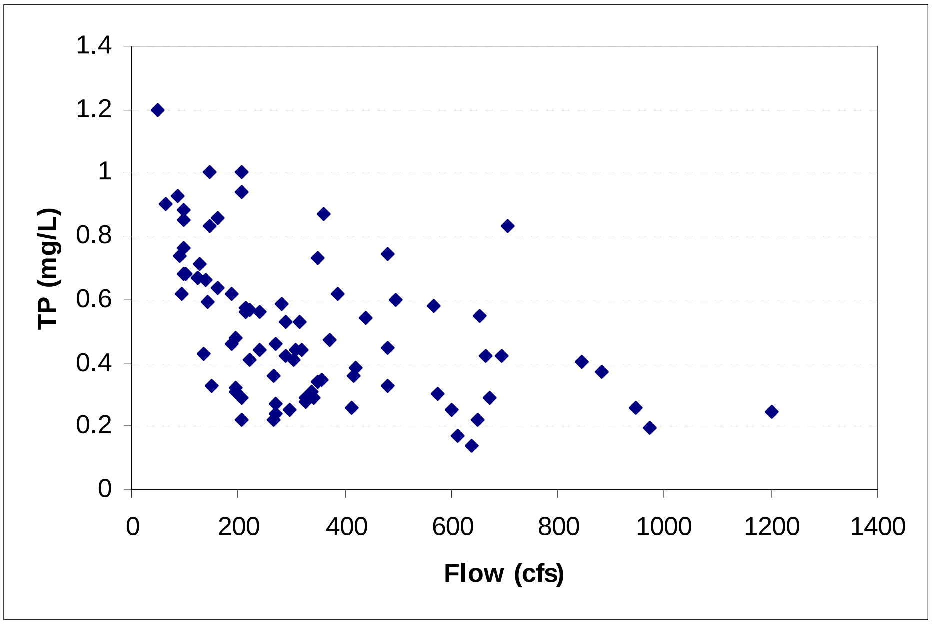


Figure 4-54. Relationship of total phosphorus concentration to flow, MCES monitoring, Upper Vermillion River at Hastings, 1995—2003.

Phosphorus loading analysis was conducted with the FLUX model (Walker, 1987), as was done for TSS. Because of the strong relationship to flow, regression methods of estimation work well for total phosphorus. No significant trends were identified with year or month; however, flow stratification does improve the coefficient of variation of estimates. Stratification at 275 hm^3/yr (246 cfs) was selected as an appropriate breakpoint between predominantly dilutional loads and surface runoff loads. Walker's "REG-3" model, , which is a log-log regression model applied to individual daily flows, was selected for the analysis. Continuous flow records were available for 1994–2002. Observed and FLUX-predicted concentrations using a 14-day interpolation window are shown in Figure 4-55; the daily load series produced by FLUX is shown in Figure 4-56. The average load estimated by FLUX is 78,353 kg/yr (86.4 t/yr) at an average flow-weighted concentration of 0.58 mg/L. This load is equivalent to a loading rate of 1.09 kg/ha; however, a significant portion of the load under current conditions is derived from the Empire WWTP. During 2003, this facility discharge upwards of 55,000 kg of total phosphorus to the Upper Vermillion. While some of this load is undoubtedly retained in the stream system during transit, it is likely that discharge from the Empire Plant accounts for well over half of the phosphorus load observed at Hastings.

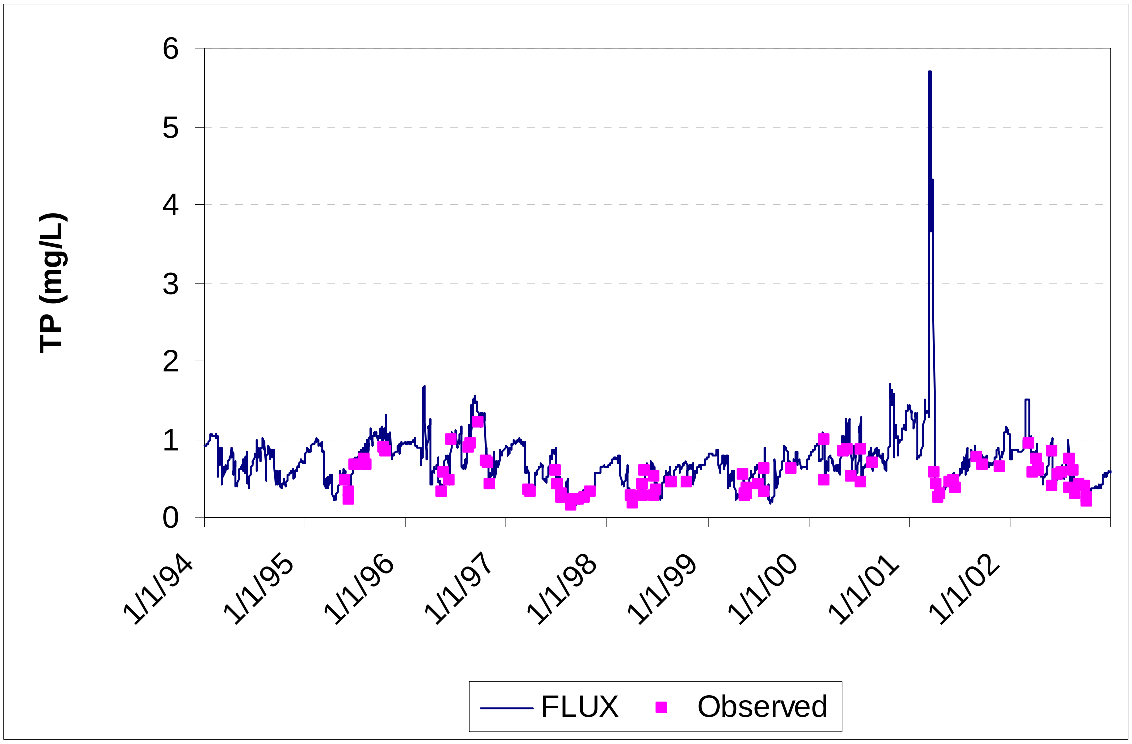


Figure 4-55. Observed and FLUX-interpolated total phosphorus concentrations at Hastings.

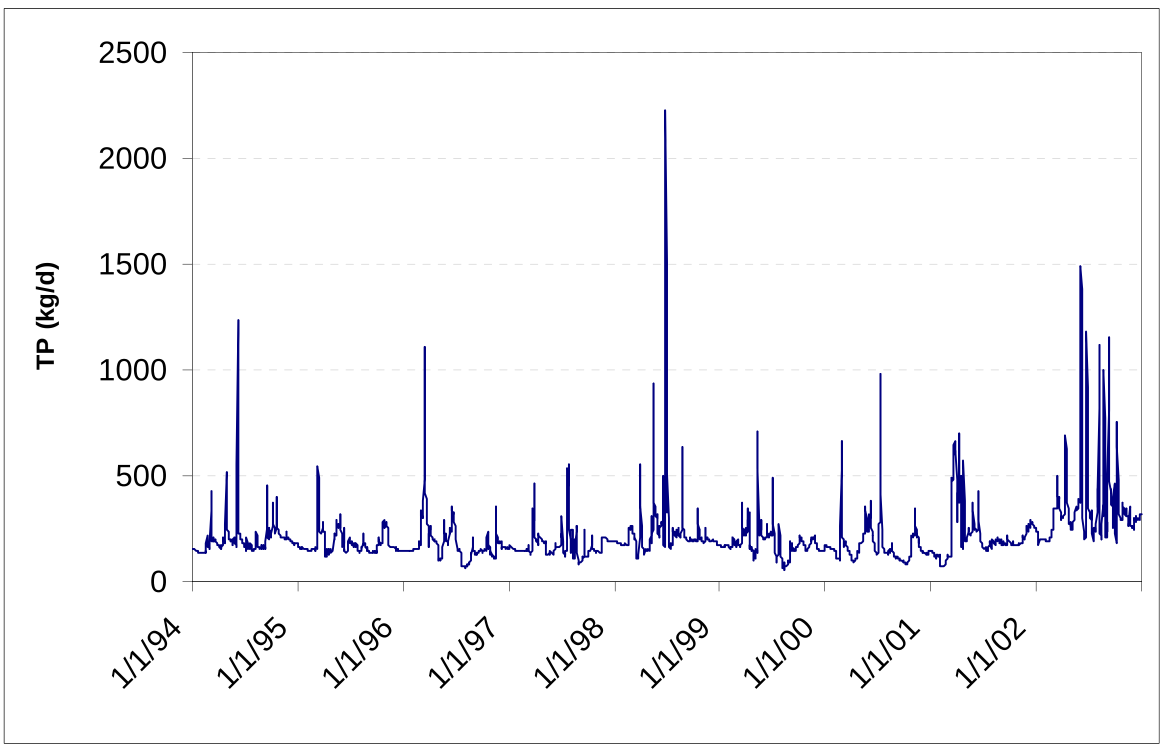


Figure 4-56. FLUX daily load estimates for total phosphorus, Upper Vermillion River at Hastings.

4.4.3 Algal Loading from the Upper Vermillion River

The Upper Vermillion River between Empire and Hastings, Minnesota has high phosphorus concentrations (average 0.62 mg/L) and, along some segments, ample light availability to induce algal growth. Thus, the Upper Vermillion might carry a significant amount of algal biomass before it reaches the LVR. Observations by Met Council on chlorophyll *a* at Empire from 1985 to 1992 (station MWCC054) show moderate chlorophyll *a* concentrations ranging from 0.7 to 28 µg/L, with an average of 5.5 µg/L. Concentrations at and near Hastings appear to be generally higher: Sampling by Met Council at Hastings (MWCC055) for 1990–1991 (only 70 samples) had an average of 11.23 µg/L with a maximum of 72 µg/L.

4.4.4 Phosphorus Loading from Local Tributaries to the LVR

No information is available on phosphorus concentrations in the local tributaries draining directly to the LVR. Furthermore, the load estimates for the Upper Vermillion at Hastings are not relevant to the local tributaries because the Hastings loads are influenced by the Empire WWTP. Model simulations in the adjacent portions of the Minnesota River watershed (Tetra Tech, 2002) suggest that the total phosphorus loading from conventional tillage agriculture in the region is likely on the order of 0.6–0.9 lb/ac/yr (0.7–1.0 kg/ha/yr) at the minor subwatershed scale.

Clear Lake and Rattling Springs Lake, both predominantly groundwater-fed, might provide an indication of phosphorus load associated with groundwater discharge to the LVR, although the concentration in these lakes is also affected by regeneration from lake sediments and local surface inputs. Both lakes had an average total phosphorus concentration of 0.21 mg/L in 1995–1998 sampling.

4.4.5 Loading from Mississippi Pool 3: Comparison to Upper Vermillion

As with TSS, a comparison of concentrations in the Upper Vermillion at Hastings and Mississippi Pool 3 is useful to determine which source of flow to the Lower Vermillion tends to dilute the other. All available stations within Pool 3 were pooled for this analysis.

The total phosphorus concentrations at the two locations for 1990 to present are shown in Figure 4-57. The plot provides individual data points, as well as a 5-point moving average. Concentrations of total phosphorus in the Upper Vermillion clearly tend to remain higher than those in Mississippi Pool 3. This is presumably because the greater fraction of urban runoff and wastewater (Empire WWTP) in the Vermillion, plus a greater percentage of urban and agricultural land use in the watershed as opposed to the entire upper Mississippi watershed. In any case, mixing of flow from the Mississippi should tend to dilute phosphorus concentrations in the LVR.

In summary, periods in which the water source in the LVR shifts from Upper Vermillion River to Mississippi Pool 3 inflow tend to correspond with reduced phosphorus concentrations in inflows to the system.

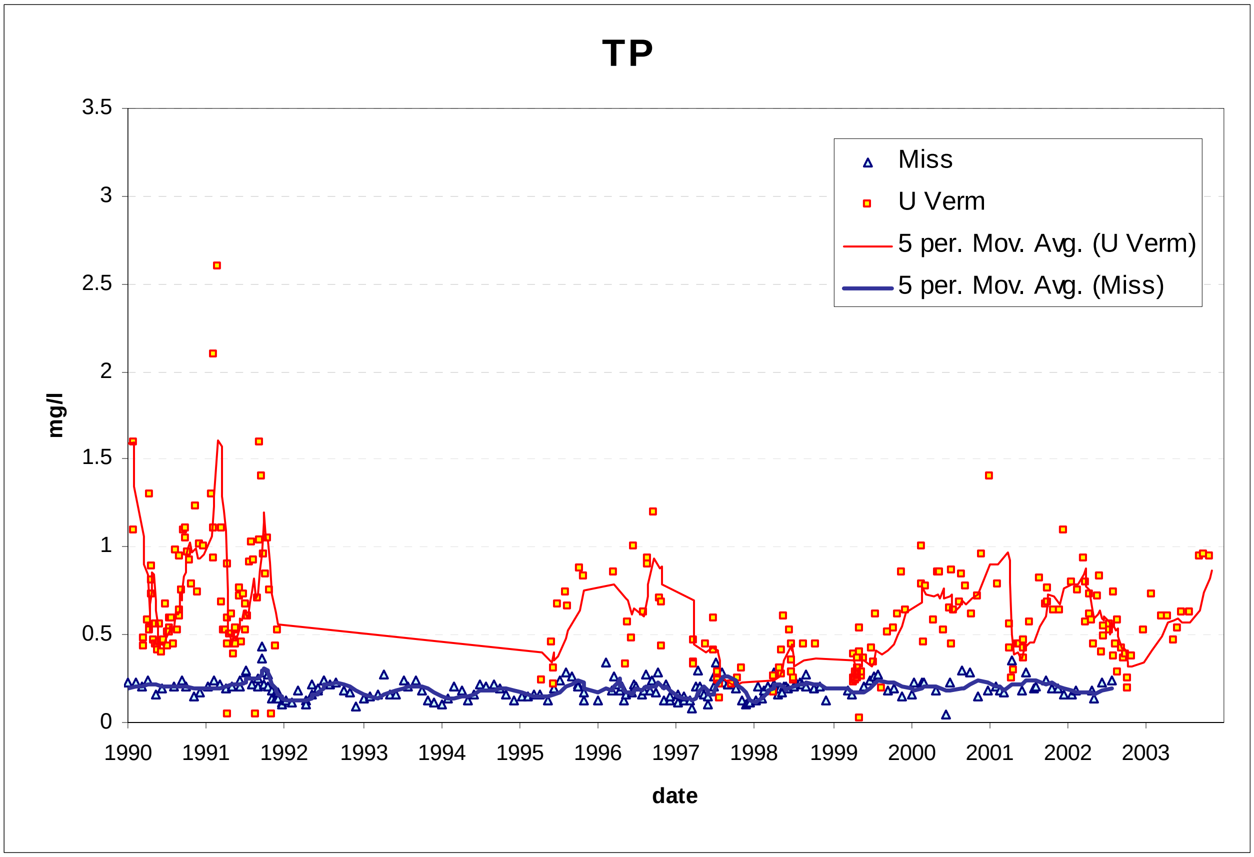


Figure 4-57. Comparison of total phosphorus concentrations in the Upper Vermillion River at Hastings and Mississippi River Pool 3.

Basic statistics on total phosphorus concentrations in Pool 3 and the Upper Vermillion are provided in Table 4-15. The medians and means are in close agreement within each individual system, and the total phosphorus concentration in the Upper Vermillion appears to be about 2.7 times the concentration in Pool 3.

Table 4-15. Total Phosphorus Statistics for Mississippi Pool 3 and Upper Vermillion River at Hastings, 1995–2003

	Mean	Median
Mississippi Pool 3	0.19	0.19
Upper Vermillion River	0.53	0.51

4.4.6 Internal Recycling of Phosphorus

Much of the phosphorus entering freshwater systems is already sorbed to particulate matter. Under oxic conditions, dissolved phosphorus in the water column tends to complex with iron oxides and other clay minerals, forming insoluble precipitates. The net result is that phosphorus tends to move from the water column to the sediment. If, however, anoxic reducing conditions exist at the sediment-water interface, the complexation reactions reverse and microbial reduction of ferrous hydroxides and complexes results in the release of phosphate, along with ferrous iron and manganese, into the water column.

In most cases, depletion of the oxidized microzone at the sediment surface first requires establishment of stratification in the water column and reduction of oxygen transport from the atmosphere to the bottom water layers. Because some flow is maintained in the LVR under most conditions by the Truedale Culvert, while the lakes in the system are apparently shallow and subject to wind mixing, it is unlikely that chemical regeneration of phosphate from the sediment is a significant process relative to the upstream loads. However, few data are presently available to test this hypothesis.

In addition to chemical regeneration, phosphorus is cycled back out of the sediments to the water column by benthic algae and rooted macrophytes. Finally, some algal species are able to indulge in "luxury consumption" of phosphorus, in which they take up more phosphorus from the water column than is needed to meet immediate growth needs and store this phosphorus reserve for later use.

4.4.7 Phosphorus Conceptual Model for the LVR

Although a complete sediment budget cannot be estimated for the LVR at this time, scoping-level estimates can be provided (Table 4-16). The method is analogous to that used for sediment because phosphorus primarily moves with sediment. The following assumptions are made:

- Load from the Upper Vermillion River is represented by the FLUX results, averaging 6,143 t/yr.

Load from Mississippi Pool 3 can be estimated as the ratio of flow from Pool 3 into the LVR to flow from the Upper Vermillion River, times the ratio of concentration (Upper Vermillion is 2.7 times Pool 3 phosphorus).

- Load from local tributaries can be roughly approximated using a per-acre yield of 0.6 lb/ac/yr.
- Load from channel erosion is not known at this time but is likely small relative to external loads.
- Groundwater contributions of phosphorus are assumed to be small because phosphorus is readily sorbed within the soil matrix.

Table 4-16. Scoping-Level Estimates of Phosphorus Inputs to the LVR

Source	Average Load (tons per year)	Percentage
Upper Vermillion River	86.4	37
Mississippi Pool 3	129.6	56
Local Tributaries	15.0	7
Channel Erosion	small (?)	?
Total	231.0	

Note: Total and percentages are calculated without channel erosion component.

The Upper Vermillion is estimated to be a more important source of phosphorus than of sediment, reflecting the contributions of the Empire WWTP (which is, however, slated to be diverted to the Mississippi). Inflows from the Mississippi still dominate the total load balance; however, under low-flow conditions, the current phosphorus load in the Upper Vermillion likely controls conditions in the LVR. Diversion of the Empire discharge is likely to reduce Upper Vermillion contributions by more than half, and is likely to result in reduced algal response in the LVR.

5 RECOMMENDATIONS

Phase I of this project has assessed the existing data for the LVR and developed a conceptual model of important processes. Based on the results of Phase I, Phase II will include additional data collection and development of modeling tools. These tools will then provide the basis for developing TMDL allocations and implementation strategies in Phase III.

This section of the document describes three options for developing a modeling tool with which to more fully assess turbidity conditions in the LVR and evaluate potential control scenarios. Recommendations for additional sampling are also provided, organized according to the type of modeling tool to be developed.

The advantages and disadvantages of each of the three potential approaches are summarized in Table 5-1. The first is a simplified approach that is generally consistent with the concepts, schedule, data collection efforts, and approximate budget described in the Statement of Work. The second approach is very similar to the first, but provides a somewhat more detailed analysis of sediment and algal interactions. The third approach is a more rigorous and complex modeling effort that would require additional time and an increased budget to complete. Use of the third approach would provide a stronger scientific and technical basis for completing the project. However, from a practical point of view, the simpler approaches may be adequate to address the pertinent questions related to the sources and nature of the turbidity impairment.

Table 5-1. Advantages and limitations of the three proposed approaches.

Approach	Advantages	Limitations
Simple Approach: Daily Flow Balance Model Coupled with WASP	• Consistent with existing schedule and budget • Smallest LOE requirement • Direct incorporation of site-specific characteristics of sloughs • Will meet the regulatory needs of the TMDL	• WASP will not predict increased light availability due to a decrease in TSS/sediment and thus will have limited use for scenario analysis • Code modifications required to simulate algae and sediment simultaneously • May be difficult to calibrate without considering momentum (i.e., hydrodynamic modeling)
Middle Approach: Integrated Hydrologic/Water Quality CE-QUAL-W2 Modeling	• Consistent with existing schedule and budget • CE-QUAL-W2 will predict increased light availability due to a decrease in TSS/sediment • Should result in a better calibration • Will meet the regulatory needs of the TMDL	• Simplifies some important physical processes, such as sediment scour and algal growth • Assumes the system is P-limited and therefore does not consider full DO/nitrogen cycle • Code modification required to address reversing flow in Vermillion Slough
Complex Approach: Hydrodynamic Modeling Coupled with Detailed Water Quality Model	• Simulates sediment transport, sediment diagenesis, and eutrophication explicitly • Provides the most realistic representation of the system, and thus the highest level of defensibility	• Will require additional time and data and larger budget

5.1 Simple Approach: Daily Flow Balance Model Coupled with WASP

The three candidate approaches are distinguished at the most basic level by their treatment of the movement of water. The simple approach can be characterized as a hydrologic model that represents the mass balance of water in the system at a daily time step. This simplified approach conserves mass but does not consider the conservation of momentum; that is, it will not provide a detailed description of the distribution of velocities or the shear stresses that cause channel and bank erosion. The middle and complex approaches would involve development of a hydrodynamic model of the system, balancing both mass and momentum. The complex approach would additionally represent sediment erosion and deposition and would need to be operated at a time step of minutes rather than days and at a much finer spatial scale.

The simplified approach would contain two main components: a daily flow balance and a daily mass balance of water quality constituents. The daily flow balance would involve the following steps:

- Segment the LVR at a coarse scale (e.g., approximately 1-mile increments), separating important tributaries and features.
- Characterize the channel (width, length, elevation, grade) within each segment and refine analysis of the hydraulic controls affecting interflow with the Mississippi.
- Use simplified rainfall/runoff models (e.g., SWAT) to estimate daily flow inputs from direct tributaries to the LVR.
- Develop engineering equations to predict approximate groundwater discharge to the LVR.
- Use the techniques described in Section 4 of this report to develop daily estimates of flow, stage, and volume in each segment of the system based on recorded stage in the Mississippi River, flow in the Upper Vermillion at Hastings, and the estimated tributary and ground water inputs.

The hydrologic balance model could be implemented either in a specially created computer program or in a spreadsheet. Because of the unique nature of the interflow between the Mississippi and the LVR, creating a model would probably be simpler than modifying an existing model.

The water quality mass balance model would be built atop the flow fields established by the hydrologic balance model and would use the same segmentation. Required components of the water quality model are established by the conceptual model of the system presented in Chapter 4. There it was determined that much of the water in the LVR originates from the Mississippi and that the most important factor in observed turbidity is inorganic solids. Therefore, a primary focus of the modeling must be the transport of solids, including solids transported from the Mississippi, from the Upper Vermillion, and from local tributaries and generated in the system by resuspension. Algal growth appears to be a secondary factor in turbidity, but it must also be addressed. This will require, at a minimum, simulation of phosphorus in the system. The simplified water quality model would have the following components:

- External loads from the Upper Vermillion would be based on observed flow and concentration at Hastings.
- External loads from the Mississippi would be based on observed concentrations and estimated flows through the sloughs.

- External loads from local tributaries would be estimated using the watershed model developed for the hydrology.

- The flow balance created for the segments of the LVR would be used to move sediment and phosphorus mass through the system, with an appropriate sedimentation loss term.

- Sediment resuspension by wind action in lakes would be estimated externally with simple engineering calculations and specified as an external input to the model.

- Channel and bank scour would also be estimated using simple external calculations based on flow regime.

- Algal concentration response would also need to be simulated, at least in approximate terms.

Because of the need to integrate mass balances for a number of constituents, it will be desirable to use a preexisting water quality model to implement the pollutant mass balance and algal response. The Water Quality Analysis Simulation Program (WASP) is the recommended model, although some code modification would be needed to adapt WASP to provide sediment transport and algal response simulation simultaneously.

5.2 Middle Approach: Integrated Hydrologic/Water Quality CE-QUAL-W2 Modeling

The middle approach is very similar to the Simple Approach but would rely on the use of the USACE's integrated CE-QUAL-W2 model to simulate both hydrology and water quality. Some code enhancement may be needed to address the specifics of flow through the sloughs, particularly the reversing flow in Vermillion Slough. Sediment would be partially simulated (not full transport), as would algae growth (the full DO/nitrogen cycle would not be simulated). In particular, CE-QUAL-W2 does not simulate sediment resuspension, which would need to be specified externally. Use of the CE-QUAL-W2 model will provide slightly more information on river flow velocities than the simple approach, although it will be operating at large spatial increments and forced by daily inputs and thus will not include detailed hydrodynamics. Relative to the simple approach, CE-QUAL-W2 provides the advantage of using a tested and widely accepted model – although some code modification will likely still be needed.

5.3 Data Needs for Simple and Middle Approach

Either of the first two approaches would need to rely on historical data for calibration of the water quality model. Some data would be collected to check performance against current conditions, but we do not anticipate collecting intensive, synoptic data for a full validation under the scope of this approach.
The following data needs have been identified as necessary for development of either the simple or middle approach.

- Reactivate the staff gage established at Etter Bridge by DNR in 1998. Record the stage daily for a sufficient period to provide a validation check on the flow balance. If the old gage has been removed, a new staff gage should be installed.

- Measure low and high flow velocities at Etter Bridge. These flow data will be used to populate and verify the derived rating curve. The water balance model can be used to estimate flows at given stages for backwater effect scenarios.

- Channel cross sections are needed on the LVR near the confluence of the three major sloughs so that stage, as well as corresponding discharge, can be calculated accurately. The three cross sections should be located on the LVR just downstream of the slough confluences. The approximate locations of Carter, Truedale, and Vermillion sloughs are river miles 12.5, 13.5, and 19.0. Additional cross sections should be collected to characterize the main channel at a density of approximately one per mile.

- The geometries of the Carter and Vermillion slough dikes are needed to determine flows over the structure. In particular, the dimensions of the crest (crest length, width, and side slopes) are needed.

- A survey of the abandoned Three Bridge Dike is needed to determine how much grade control the remnants of this structure provide in the LVR below Vermillion Slough. If a dike (possibly Spot Dike K or DNR Dike") controls the flows between Mudhen Lake and the LVR, the geometry of the dike will also be needed to calculate flows through Carter Slough.

- The elevations of the inlet and outlet of the Truedale Slough culvert are needed to determine the magnitude of flows through the culvert.

- Additional water quality data are needed to better characterize conditions throughout the LVR. Existing stations MS297, MS299, MS221, S001-227 and S001-229 (selection of stations to be finalized after discussions with MPCA) should be sampled monthly throughout the summer for discharge, field parameters (turbidity, pH, temperature, color), dissolved P, TP, TSS, chlorophyll *a*, and TVS.

- Particle-size distributions should be determined for on-channel and off-channel lake sediments to estimate resuspension potential. These samples can also be analyzed for phosphorus and, if MPCA desires, for PCBs (to support Task 10).

5.4 Complex Approach: Hydrodynamic Modeling Coupled with Detailed Water Quality Model

A more sophisticated approach would involve creating of a full hydrodynamic model of the LVR that can explicitly account for flow momentum, scour, and the effects of wind stress. Such a model would also allow a more sophisticated evaluation of flow over the dikes. A full hydrodynamic simulation is likely to require a time step on the order of minutes and a relatively fine spatial scale. The selection of candidate models is somewhat limited by the need to consider reversing flows at Vermillion Slough Dike.

The hydrodynamic model would in turn be linked to a more sophisticated water quality model—preferably one designed for integral linkage with the hydrodynamics—that could simulate sediment scour and deposition, including wind-induced turbulence, on a process basis, as well as chemical water quality data and algae on a daily time step. The algal simulation should address nitrogen species in addition to phosphorus and light. EFDC is one model that fits these characteristics. It is also possible to use EFDC hydrodynamics to link to the WASP water quality model, which would be implemented at a higher level of complexity than that in the simple approach.

The types of models discussed in this section have more intensive data requirements than the simple approach. In addition, to achieve the advantages of the more complex water quality simulation, it would be necessary to collect some new comprehensive data sets for model calibration and validation. These should include synoptic data that can test model performance in both space and time.

5.5 Additional Data Needs for Complex Approach

All the data specified for the simple/middle approaches would also be needed for the complex approach. In addition, the following data would be needed to fully calibrate a more advanced hydrodynamic/water quality model:

- Record the stage at Etter Bridge continuously during the second phase of the project.
- Measure low and high flow velocities at two additional locations (besides Etter Bridge). These flow data will be used to calibrate the hydraulic/hydrodynamic model. A time-of-travel study in the LVR mainstem should be evaluated as a further calibration tool.
- Add staff gages at County Highway 18 and at or near the confluence of the Cannon River and the LVR. Record stage continuously during the period of water quality data collection.
- Extend channel surveys to provide a more detailed estimate of channel dimension throughout the LVR, and also survey the sloughs and on-line lakes.
- Conduct time-of-travel studies through the LVR.
- Collect synoptic water quality data. Such data are needed to better characterize conditions throughout the LVR. Existing stations MS297, MS299, MS221, S001-227, and S001-229, (selection of stations to be finalized after discussions with MPCA) as well as Clear Lake and Goose Lake, should be sampled twice monthly throughout the summer for field parameters (turbidity, pH, temperature, color, Secchi depth, light penetration), dissolved P, TP, TSS, nitrogen series, chlorophyll *a*, and total and dissolved volatile solids.
- Conduct wet-weather water quality sampling of Etter Creek for discharge and the full suite of nutrients, TSS, and chlorophyll *a*.
- Algal growth potential tests at selected sites in the LVR and lakes would be useful to better constrain the algal response model.
- Perform critical shear stress testing of sediment in on-channel lakes.

5.6 Recommended Approach

Based on additional discussions with MPCA and comments received on the draft Phase I report, we are recommending our Middle Approach: Integrated Hydrologic/Water Quality CE-QUAL-W2 Modeling. This middle approach is recommended for the following reasons:

- Consistent with existing schedule and budget
- CE-QUAL-W2 will predict increased light availability due to a decrease in TSS/sediment
- Should result in a better calibration than the simple approach
- Will meet the regulatory needs of the TMDL
- Does not require separation of the hydrodynamic and water quality modeling
- Provides the advantage of using a tested and widely accepted model – although some code modification will likely still be needed.

5.7 Role of Volunteer Monitoring

The Citizen Stream Monitoring Program (CSMP) is an important part of MPCA's efforts to develop a more comprehensive statewide monitoring network. Persons in the CSMP devote their time and energy to conduct simple stream checks by visiting an established spot approximately once a week during the summer to measure the following:

- Transparency (using a transparency tube)
- Appearance (water color)
- Recreational suitability (very good to poor)
- Precipitation
- Stream stage (low, normal, or high)

Limited volunteer monitoring has thus far been conducted on the LVR, but several individuals have expressed interest in participating in the program this summer. Such participation might be very useful in helping to complement the data to be collected during the Phase II sampling. The following recommendations are made regarding the role of volunteer monitoring:

- The usefulness of the volunteer monitoring data will depend on how well the volunteers are trained and provided with proper equipment. MPCA should provide training to the participants who volunteer for the LVR sampling.
- The usefulness of the data would be enhanced if MPCA could supply a calibrated field nephelometer to the volunteers, rather than relying solely on transparency tubes.
- More information on light penetration would also be useful. This is relevant to submerged aquatic vegetations preservation, and also relates indirectly to relative turbidity. Ideally these data would be collected with a photometer, but simple Secchi disk readings would be potentially useful. Both time series of observations at particular locations and longitudinal surveys of Secchi depth might be useful.
- The most useful information would be data for the LVR between Hastings and the mouth, where few data have been collected in the past. Information upstream and downstream of the sloughs would also be very useful.
- If possible, the volunteers should attempt to obtain some longitudinal surveys from Hastings to the mouth of the LVR. Good location data would be needed for these data, either through the use of a global positional system (GPS) or a detailed map.

REFERENCES

Allen, J.D. 1995. *Stream Ecology: Structure and Function of Running Waters.* Kluwer Academic Publishing, The Netherlands.

Austin, R.W. 1974. Problems in measuring turbidity as a water quality parameter. In *Proceedings of a Seminar on Methodology for Monitoring the Marine Environment*. EPA-600/4-74-004. U.S. Environmental Protection Agency, Washington, DC.

Baker, A.L., and K.K. Baker. 1979. Effects of temperature and current discharge on the concentration and photosynthetic activity of the phytoplankton in the Upper Mississippi River. *Freshwater Biol.* 9:191–198.

Bohlen Surveying. 2002, July 30. Letter from Gary Bunkers, P.E., Bohlen Surveying and Engineering, Northfield, MN, to Brian Watson, Dakota County Soil & Water Conservation District, Farmington, MN.

Bowie, G.L., W.B. Mills, D.B. Porcella, C.L. Campbell, J.R. Pagenkopf, G.L. Rupp, K.M. Johnson, P.W.H. Chan, S.A. Gherini, and C.E. Chamberlin. 1985. Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (2nd ed.). EPA/600/3-85/040. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

Bronmark, C., and L.A. Hansson. 1998. *The Biology of Lakes and Ponds.* Oxford University Press, New York.

Carlson, R.E. 1980. More complications in the chlorophyll-Secchi disk relationship. *Limnology and Oceanography* 25:378–382.

Chesapeake Bay Program. 2000. Factors contributing to light attenuation. Chapter 4 in *Chesapeake Bay Submerged Aquatic Vegetation Water Quality and Habitat-based Requirements and Restoration Targets: A Second Technical Synthesis.*

Cochran, W.G. *Sampling Techniques*. 3rd ed. John Wiley and Sons, New York.

Cowdery, T.K. 1999. Water Resources of the Prairie Island Indian Reservation, Minnesota, 1994–97. Water-Resources Investigations Report 99-4069. U.S. Geological Survey, Mounds View, MN.

Dakota County SWCD (Soil and Water Conservation District). 2002. Etter Creek Watershed Assessment and Bank Restoration Project, Interim Report. Dakota County Soil and Water Conservation District, MN.

———. 2003. Etter Creek Watershed Assessment and Bank Restoration Project, Final Report. Prepared by Dakota County Soil and Water Conservation District, MN in cooperation with Ravenna Township.

Dieterman, D. 1995. Major River Survey, Upper Mississippi River Pools 3, 5, 5A, 6, 7, upper 9, and LVR. Minnesota Department of Natural Resources. Lake City, MN.

———. 1995. Stream Survey Report, Major River Survey, Backwaters of Upper Mississippi River Pools 3, 5, 5A, 6, and 9, and LVR, 1995. Minnesota Department of Natural Resources, Division of Fish and Wildlife, Section of Fisheries.

———. 2002. Major River Survey, Upper Mississippi River Pools 3, 5, 5A, 6, 7, upper 9, and LVR. Minnesota Department of Natural Resources. Lake City, MN

FHWA (Federal Highway Administration). 1983. Hydraulic Design of Energy Dissipators for Culverts and Channels. FHWA EPD-86-10, HEC 14. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

———. 1984. Hydrology. FHWA-IP-84-15, HEC 19 (E). Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

———. 1985. Hydraulic Design of Highway Culverts, FHWA-IP-85-15, HDS 5. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Fogg, G.E. 1987. *Algal Cultures and Phytoplankton Ecology*. 3rd ed. University of Wisconsin Press, Madison, WI.

Gallegos, C.L. 2001. Calculating optical water quality targets to restore and protect submersed aquatic vegetation: Overcoming problems in partitioning the diffuse attenuation coefficient for photosynthetically active radiation. *Estuaries* 24(2):381–397.

Gallegos, C.L., and P.J. Neale. 2002. Partitioning spectral absorption in case 2 waters: Discrimination of dissolved and particulate components. *Applied Optics* 41(21):4220–4233.

Heiskary, S. 1999, May 7. Observations on Vermillion River floodplain lakes water quality survey: 1998 data. Memorandum from Steve Heiskary, Minnesota Pollution Control Agency, to Walt Popp, Minnesota Department of Natural Resources.

Henley, W.F., M.A. Patterson, R.J. Neves, and A. Dennis Lemly. 2000. Effects of sedimentation and turbidity on lotic food webs: A concise review for natural resource managers. *Reviews in Fisheries Science* 8(2):125–139.

Hoffman, R., and K. Kearns, eds. 1997. *Wisconsin Manual of Control Recommendations for Ecologically Invasive Plants*. Wisconsin Department of Natural Resources, Madison, WI.

Johnson, Scot. 1996, January 4. Preliminary Vermillion River Bottoms Hydrologic Analysis. Memorandum from Scot Johnson, MNDNR Waters, Lake City, MN, to Mike Davis, MNDNR Ecological Services, Lake City, MN.

———. 1998, March 11. Letter from Scot Johnson, DNR Waters Lake City Area Office, to Steve Heiskary, MPCA, St. Paul, MN.

———. 1999, January 22. Vermillion River Stage/Discharge Data. Memorandum from Scot Johnson, MNDNR Lake City, to Steve Heiskary, MPCA, St. Paul, MN.

Lenat, D.R., D.L. Penrose, and K.W. Eagleson. 1981. Variable effects of sediment addition on stream benthos. *Hydrobiologia* 79:187–194.

Lloyd, D.S., J.P. Koenings, and J.D. LaPerriere. 1987. Effects of turbidity in freshwaters of Alaska. *N. Am. J. Fish. Manage.* 7:18–33.

MNDNR, 1990. Minnesota Land Use and Land Cover: 1990 Census of the Land.

Newcombe, C.P., and J.O.T. Jensen. 1996. Channel suspended sediment and fisheries: A synthesis for quantitative assessment of risk and impact. *N. Am. J. Fish. Manage.* 16:693–627.

Preston, S.D., V.J. Bierman, Jr., and S.E. Silliman. 1989. An evaluation of methods for the estimation of tributary mass loads. *Water Resources Research* 25(6):1379–1389.

SCS (Soil Conservation Service). 1978. Inventory and Evaluation of Natural Resources and Related Problems in the Etter Creek Watershed. Soil Conservation Service, U.S. Department of Agriculture.

Tetra Tech. 2002. Minnesota River Basin Model, Model Calibration and Validation Report. Prepared for the Minnesota Pollution Control Agency by Tetra Tech, Inc., Research Triangle Park, NC.

Thackston, E.L., and M.R. Palermo. 2000. Improved Methods for Correlating Turbidity and Suspended Solids for Monitoring. DOER Technical Notes Collection ERDC TN-DOER-E8. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

UMRCC (Upper Mississippi River Conservation Committee). 2003. Proposed Light-Related Water Quality Criteria Necessary to Sustain Submersed Aquatic Vegetation in the Upper Mississippi River. Upper Mississippi River Conservation Committee, Water Quality Technical Section, October 2003.

UMRSEMP (Upper Mississippi River System Environmental Management Program). 1990. Goose Lake Water Level Control Habitat Rehabilitation and Enhancement Project, Pool 3, Upper Mississippi River, Dakota and Goodhue Counties, Minnesota. Upper Mississippi River System Environmental Management Program, Definite Project Report/Environmental Assessment (SP-6). U.S. Army Corps of Engineers, St. Paul District.

USACE (U.S. Army Corps of Engineers), 1987. Truedale Slough Dike Final Inspection Photo Log.

———. Date Unknown. Definite Project Report/Environmental Assessment. Pool 3/Upper Pool 4 Channel Management Plan. Dpr Drawing No. M34-T-Cc/Fno.01, Plate 21.

———. 1936. Dikes at Vermillion and Carter Sloughs Plan and Details. War Department, Corps of Engineers U.S. Army. Sheet No. M-L3 - 52/26.

———. 1986. Maintenance - Mississippi River Pool 3 - Dakota County, Minnesota. Truedale Slough Dike. Typical Sections of Channel. May 1986. Drawing # M-L3-52/42 and Drawing # M-L3-10/54. Sheets 2 and 7 of 11. Department of the Army. St. Paul District, Corps of Engineers. St. Paul, Minnesota.

———. 1987. Dike Evaluation, Pool No. 3, Mississippi River, Minnesota and Wisconsin, Appendix A.

USGS (U.S. Geological Survey). 2000. *Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data*. By J.R. Gray, G.D. Glysson, L.M. Turcios, and G.E. Schwarz. Water-Resources Investigations Report 00-4191.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37:130–137.

Vanoni, V.A., ed. *Sedimentation Engineering*. American Society of Civil Engineers, New York.

Walker, W.W., Jr. 1987. Empirical Methods for Predicting Eutrophication in Impoundments, Report 4, Phase III: Applications Manual. Technical Report E-81-9. U.S. Army Corps of Engineers, Washington, DC.

Waters, T.F. 1995. *Sediment in Streams: Sources, Biological Effects and Controls.* American Fisheries Society Monograph 7. : American Fisheries Society, Bethesda, MD.

Wilde, F.D., and J. Gribs. 1998. Turbidity. Chapter 6.7 in *National Field Manual for the Collection of Water-Quality Data*. Techniques of Water-Resources Investigations Book 9. U.S. Geological Survey. Available online at http://pubs.water.usgs.gov/twri9a6.

Winterstein, T.A. 2000. Water-Quality Data Collected on Prairie Island near Welch, Minnesota, 1998–99. Open-File Report 00-78. U.S. Geological Survey, Mounds View, MN.

APPENDIX A: HY8 RESULTS SUMMARY FOR TRUEDALE SLOUGH CULVERT AND DIKE (ELEVATION IN NGVD 1912)

Appendix B

Lower Vermillion River – Turbidity TMDL Project: Modeling Report

Final Draft

October 30, 2007

Prepared for

Minnesota Pollution Control Agency

Prepared by

Tetra Tech, Inc.

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1.0 INTRODUCTION

The Vermillion River from Hastings to the confluence with the Mississippi River, referred to as the Lower Vermillion River (LVR), is included on Minnesota's Clean Water Act Section 303(d) list of impaired waters for turbidity. Water quality monitoring of the LVR has shown that its turbidity levels frequently exceed the Minnesota Pollution Control Agency's (MPCA) criterion of 25 Nephelometric Turbidity Units (NTU). As required by the Clean Water Act, MPCA has initiated development of a total maximum daily load (TMDL) to address the turbidity impairment. The purpose of developing a TMDL is to identify the pollutant loading that a waterbody can receive and still achieve water quality standards.

The goals of the LVR Watershed Turbidity TMDL Project are to describe the nature and extent of turbidity in the highly complicated setting of the LVR; determine the linkage between turbidity and sediment and nutrient loading sources; and produce a final report that expresses potential solutions to the turbidity problem in terms of an "allocation" among sources and recommendations for corrective actions.

Due to the complexities of the system, the project is being implemented in three phases:

1) Phase I: Data Gathering and Development of Conceptual Model
2) Phase II: Sampling and Model Development
3) Phase III: Model Refinement and TMDL Development

Phase I involved data gathering and development of a conceptual model and the details of this analysis are presented in the Phase I report (Tetra Tech, 2004). Among the most significant of the Phase I findings were the following:

- At a gross conceptual level, four modes of behavior in the LVR system can be distinguished:
  - Normal Flow (Mode 1): Stage in Mississippi River Pool 3 is low enough to prevent flow from the Mississippi to the LVR about 50 percent of the time.
  - Mississippi High Flow (Mode 2): Above this level, flow can enter the LVR from Pool 3, first via Vermillion Slough, then via Truedale and Carter Slough.
  - Upper Vermillion High Flow (Mode 3) High water in the Upper Vermillion may cause a reversal of flow through the Vermillion Slough.
  - Cannon River Flood (Mode 4): Elevated stage below Lock and Dam 3 or flood flows in the Cannon River can cause a backwater with reversal of flow into the downstream end of the LVR.
- On a long-term basis the LVR system appears to receive significantly more inflow from Mississippi Pool 3 than from the Upper Vermillion. Even when estimates of inflow from local tributaries to the LVR and groundwater discharge are added, the long-term inflow from Pool 3 is still more than twice the flow from other sources. Cumulative pollutant loading to the LVR thus depends largely on the Mississippi. However, during low to moderate flow conditions, inflow to the LVR can be dominated by its own watershed.
- The relationships between turbidity, TSS, and chlorophyll *a* were explored to begin to understand the causes of elevated turbidity in the LVR and the following tentative inferences were made:
  - Inorganic sediment appears to be the primary cause of elevated turbidity. Sources of inorganic sediment include the Mississippi River, the Upper Vermillion River, channel erosion, and local tributaries.
  - Pathways involving algae and organic detritus contribute about 38 percent (on average) of the observed turbidity in the LVR.
  - Volatile solids (algae and organic detritus) do not appear to be a major component of turbidity in Mississippi Pool 3, which is controlled by the suspended sediment load.

External loads of algae and detritus to the LVR are likely not significant contributors to the turbidity problem.
- Algal growth within the LVR is a secondary contributor to turbidity and is sensitive to concentrations of phosphorus.

Based on the Phase I findings, the primary need for more fully evaluating the turbidity problem in the LVR was determined to be the creation of a model to provide a more complete description of the movement of water in the system and to link sediment sources with turbidity impacts. A secondary need is the creation of a model to evaluate the impact of nutrients and algae. This report describes the model selection process and the results of the calibration and validation effort. The calibrated model will be used to support Phase III of this project: Model Refinement and TMDL Development.

2.0 MODEL SELECTION

MPCA and its consultant selected the U.S. Army Corps of Engineers CE-QUAL-W2 (W2) model for simulating sediment transport and phytoplankton processes in the Lower Vermillion River. W2 is a two-dimensional, longitudinal/vertical (laterally averaged), coupled hydrodynamic and water quality model (Cole and Wells, 2003). The model is applicable to lakes, rivers, and estuaries that do not exhibit significant lateral variability in water quality conditions. It allows application to multiple branches for geometrically complex waterbodies with variable grid spacing, time variable boundary conditions, hydraulic structures, and multiple inflows and outflows from point/nonpoint sources and precipitation.

Advantages to choosing W2 for the Lower Vermillion River modeling application include the following:

- W2 is able to address the pollutants of concern (e.g., total suspended solids (TSS), inorganic suspended solids (ISS), total phosphorus (TP), NH4, nitrate+nitrite (NO2NO3), dissolved oxygen (DO), and chlorophyll *a* (CHLA)). These pollutants can then in turn be used to estimate turbidity using relationships identified during the Phase I analysis.
- W2 is appropriate for a long and narrow river with spatially varying depths.
- W2 has been successfully linked in previous applications to watershed models such as the Soil and Water Assessment Tool (SWAT), which is used to estimate pollutant loads from the local tributaries to the LVR.
- W2 will predict increased light availability due to a decrease in TSS/sediment.
- W2 provides the advantage of using a tested and widely accepted model – although some code modification was needed to address the simulation of total phosphorus (see Section 3.6 for details).
- Simpler receiving water models would be limited in their ability to address the characteristics of the river (highly dynamic, open boundaries, hydraulic structures).
- Simpler receiving water models would also prove inadequate to support a more detailed analysis should additional data become available.
- W2 is capable of simulating cause-and-effect relationships between loading from various sources and river response.
- Application of W2 is consistent with the schedule and budget.

The two major components of the W2 model include hydrodynamics and water quality kinetics. Both of these components are coupled (i.e., the hydrodynamic output is used to drive the water quality at every time step). This makes it very efficient to set up model runs and avoid any external linkage which may require unreasonably high file sizes. The hydrodynamic portion of the model predicts water surface elevations, velocities, and temperature. The W2 model provides three numerical schemes for solving the advection portion of the transport equations including UPWIND, QUICKEST, and ULTIMATE-QUICKEST. The UPWIND scheme is fastest with high numerical diffusion. The ULTIMATE – QUICKEST scheme requires more computation time but has minimal numerical diffusion and dispersion. The UPWIND is used for the LVR model since no strong vertical gradients have been observed or reported. Using UPWIND instead of ULTIMATE-QUICKEST saves significant computation time with only a minimal compromise to accuracy. The water quality portion of W2 can simulate the constituents required for phytoplankton dynamics, including dissolved oxygen, nutrients, and phytoplankton interactions.

3.0 MODEL CONFIGURATION

Configuration of the W2 model involved setting up a computational grid using available bathymetry data and setting initial conditions, boundary conditions, and hydraulic and kinetic parameters for the hydrodynamic and water quality simulations. This section describes the configuration and key components of the model.

3.1 Model Segmentation

Segmentation is usually the first step to configure the W2 model. The computational grid defines how the LVR is represented in the W2 model. The main channel of the LVR is represented as the main branch in the W2 model and the following sloughs that connect the LVR and the Mississippi River were also included as tributary segments:

- Vermillion Slough
- Truedale Slough
- Carter Slough

Several lakes that connect to the LVR are also included in the model:

- Clear Lake
- Rattling Springs Lake
- Nelson Lake
- Birch Lake
- Goose Lake

Wildcat Lake, Mud Hen Lake, and Round Lake are also included in the model as part of the Carter Slough branch. The main channel, sloughs, and lakes included in the W2 model are shown in Figure 1. The shorelines of the river, and the sloughs connecting the LVR and the Mississippi River were identified with geographic information system (GIS) shapefiles and satellite images. The model boundary locations were also determined based on the available GIS data. Segmentation was conducted in ArcMap using GIS shapefiles and satellite 2000 True Color Photo Mosaics images acquired from the Upper Midwest Environmental Sciences Center (Figure 2). In the meandering portion of the river, segments are usually short and dense. In the straight portion of the river, segments are usually longer. In general, the segmentations of the lakes are coarser than the channels since the lakes mainly serve as storage basins. For developing the W2 bathymetric file, the widths of the surface layers for all the segments are calculated from the GIS shapefiles. Cross-section survey data collected during the spring of 2006 were used to develop the average channel width with a 1 meter vertical interval. In addition to the surface layer widths, the segment orientations are calculated. The Lower Vermillion River W2 model includes 14 branches, 150 segments, and 12 vertical layers. Branches 1 and 4 are the main LVR. Branches 2 and 3 are Vermillion Slough; Braches 5 and 6 are Truedale Slough; Branches 7 and 8 are Carter Slough; the rest of the branches are the lakes.

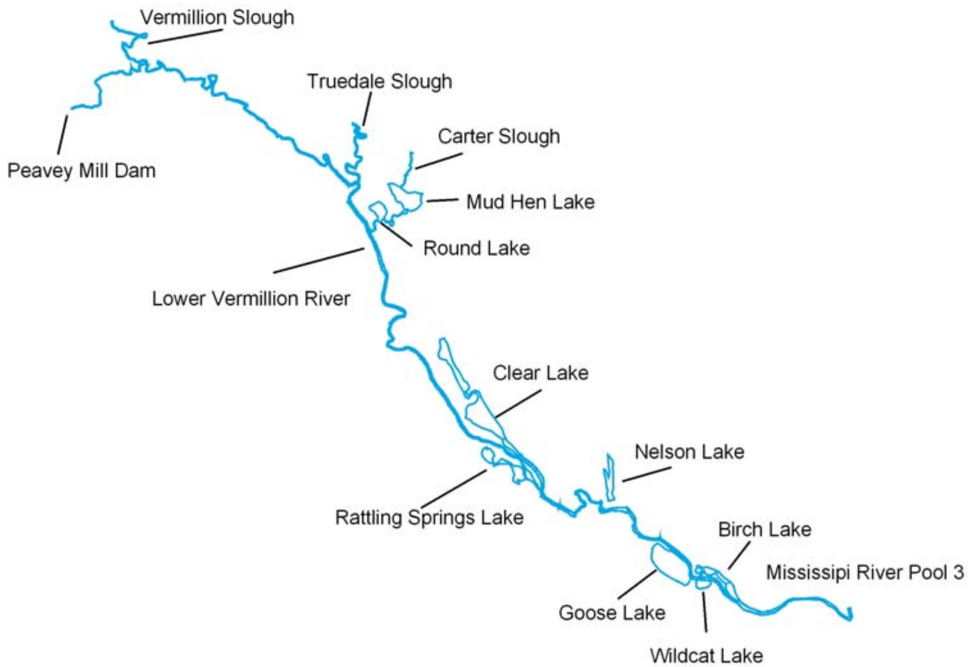


Figure 1. Lower Vermillion River W2 Model Domain

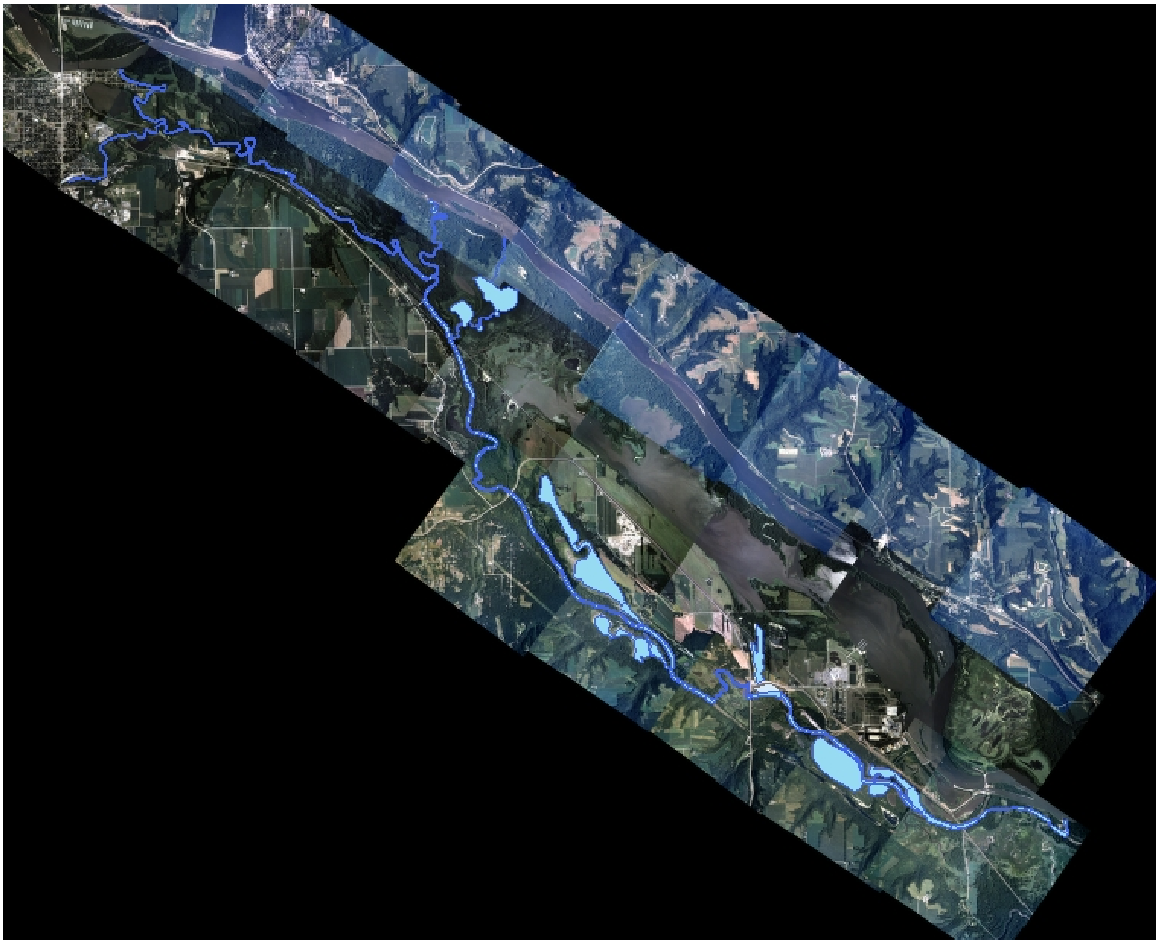


Figure 2. Satellite imagery used during the setup of the Lower Vermillion River CE-QUAL-W2 model.

3.2 Modeling Processes

The W2 model is a coupled hydrodynamics water quality model that is able to model 28 water quality state variables and up to 60 derived variables (Cole and Wells, 2003). The purpose of the LVR model application is to simulate turbidity, which is strongly related to suspended solids and algae as documented in the Phase I report (Tetra Tech, 2004). The primary goal of the LVR W2 modeling was therefore to accurately simulate suspended solids and algae. Nutrients are the major limiting factors for algae growth and thus accurate simulation of the nutrient cycle was also a goal of the modeling effort. Organic materials including dead algae consume oxygen during decomposition. The decomposition of organic materials converts nutrients in organic species to inorganic species that algae can use directly. In addition, deposited organic materials are the major cause of sediment oxygen demand (SOD). Dissolved oxygen (DO) may also impact the uptake of nutrients by algae. Therefore, the LVR W2 model simulates inorganic suspended solids (ISS), dissolved inorganic phosphorus (PO4), ammonium (NH4), nitrate (NO3), LDOM (labile dissolved organic matter), RDOM (refractory dissolved organic matter), LPOM (labile particulate organic matter), RPOM (refractory particulate organic matter), chlorophyll *a*, and DO. The main physical and biological processes include suspended sediment net settling, nutrient dynamics, algae growth, respiration, excretion, mortality, and settling.

3.3 Initial Conditions

The W2 model requires the user to specify initial temperature and water quality conditions at the start of the model run. For a 10-year simulation, the impact of initial conditions will disappear quickly due to the impacts of upstream inflows, downstream boundary conditions, and flows through the three sloughs. Therefore a constant initial temperature of 5° C (January 1995) was specified throughout the river and constant initial condition values for water quality parameters were specified. The initial water surface elevation was set to 206 meters above sea level. Algae was set to 1.0 mg/L biomass, DO was set to 8 mg/L, and other water quality variables were set to 0.001 mg/L for the initial conditions.

3.4 Boundary Conditions

Boundary conditions are required as inputs for the W2 model and represent external contributions of flow and pollutants into the river. Boundary conditions for the LVR included the following:

- Upper Vermillion River
- Mississippi River Pool 3
- Mississippi River Pool 4
- Lateral Conditions

The sections below provide a detailed description of how each of the various boundary conditions was simulated.

3.4.1 Upper Vermillion River

Flow from the Upper Vermillion River (UVR) is a major source of water and pollutants to the Lower Vermillion River and was estimated using FLUX. Appendix A provides a detailed description of the FLUX analysis.

The simulation period of FLUX is from 1995 to 2006 and the recorded flow data for this period was directly used as a boundary condition input to the W2 model. Water temperature data recorded by METC in the Upper Vermillion River at mile 2.7 and mile 15.6 were used to estimate the inflow temperature to the LVR. This assumption was deemed appropriate since water temperatures typically do not vary dramatically within one watershed.

Concentrations of nutrients and suspended solids were estimated with FLUX following the procedure described in Appendix A. FLUX outputs BOD5, NO2NO3, TKN, TP, TSS, and TVS, while W2 requires ISS, PO4, NH4, NO3, LDOM, RDOM, LPOM, RPOM and the approaches for converting the FLUX output to W2 input is summarized in Table 1.

Table 1. Approaches for converting FLUX output to W2 input.

W2 Input	Conversion
ISS	Obtained by subtracting TVS from TSS
PO4	Assumed to 85% of TP[1]
NH4 and TKN	Monthly variable ratios of NH4 to TKN were calculated using LVR monitoring data first, and TKN was converted to NH4 accordingly
NO2NO3	Assigned to NO3 directly since NO2 is usually much lower than NO3
LOM, ROM, LDOM, LPOM, RDOM, RPOM	Unfiltered CBOD5, filtered CBODu, and unfiltered CBODu data were downloaded from the MCES monitoring stations VR15.6 and 20.6. CBOD5 and CBODu data were used to estimate the labile/refractory split. Filtered CBODu and unfiltered CBODu data were used to estimate the particulate and dissolved split. After the ratios were determined, DOC (filtered TOC) data were used to estimate the LDOM, RDOM, LPOM, RPOM for W2.

[1]PO4 was originally estimated at 85% of TP based on a perceived lack of data for the Upper Vermillion River. METC clarified that filtered TP, unfiltered TP, filtered PO4, and unfiltered PO4 data were available from VR sites 2.0, 15.6, and 20.6 and these data were used to calculate ratios between PO4 and TP. The results were very similar to the original estimate of 85% and therefore that value kept.

In addition to organic materials and nutrients, W2 requires boundary conditions for algae biomass and DO, which cannot be obtained from FLUX. Since DO is able to adjust with re-aeration, the upstream boundary DO concentrations do not significantly impact the DO conditions in the LVR. A constant 10 mg/L was therefore assigned to upstream DO. The only algae data available near the upstream boundary are at Station MWCC055 from 1990 to 1991. Monthly averaged algae were calculated first and daily algae levels were interpolated using the monthly values and repeated from 1995 to 2006 as upstream algae conditions. Since local nutrient, temperature, and solar radiation conditions exhibit a strong influence on algae levels, the impact of upstream algae levels in the model disappears after several segments.

3.4.2 Mississippi Pool 3

Three major sloughs are connected with Mississippi Pool 3 along the LVR, located at Mississippi River mile points 813.2 (Vermillion Slough), 808.5 (Truedale Slough), and 807.3 (Carter Slough). At the conjunctions of Pool 3 and the sloughs, water can flow freely and elevations in Pool 3 and the sloughs determine the magnitude and direction of the flow. Therefore, elevation boundary conditions were specified for the three sloughs as upstream boundary conditions. Measured elevations in Pool 3 are available for Mississippi River miles 815.0, 811.4, and 796.91 from the U.S. Army Corps of Engineers. Linear interpolations of the elevations were used to estimate the Pool 3 elevations at the mouths of the three sloughs.

In addition to elevations, water temperature, nutrients, and suspended solids in Pool 3 are required for the LVR model. Water quality data were available from monitored conducted at Mississippi River miles 815.6, 813.9, 812.8, and 796.9. The water quality data were measured at a much lower frequency than the elevation data and different parameters were measured at different stations. Therefore, all of the available data in Pool 3 were averaged to determine boundary conditions for the sloughs. Since some water quality parameters were measured on different dates, linear interpolations of the parameters were conducted to prepare a W2 boundary condition time series file.

The monitored data include TSS, VSS, CBOD, PO4, NH4, NO3, TOC, CHLA, and DO. ISS for W2 was obtained by subtracting TVS from TSS. Unfiltered CBOD5, filtered CBODu, and unfiltered CBODu data were downloaded from station 796.9 in Pool 3 to estimate the conversion from DOC to LDOM, RDOM, LPOM, and RPOM. Filtered CBODu and unfiltered CBODu data were used to estimate the particulate and dissolved split. After the ratios were determined, DOC (filtered TOC) data were used to estimate the LDOM, RDOM, LPOM, RPOM for W2.

3.4.3 Mississippi Pool 4

LVR enters Pool 4 of the Mississippi River and Pool 4 is the downstream boundary in the W2 model. The Pool 4 elevations have a great impact on the LVR hydrodynamics and an elevation boundary condition was specified for Pool 4. Since the location of the downstream boundary is near the Pool 3 Lock and Dam and is under the impact of the Pool 3 tailwater, the Pool 3 tailwater elevations were used to establish the boundary condition.

In addition to elevations, water temperature, nutrients, and suspended solids in Pool 4 are required for the LVR model. Data collected at Mississippi River Mile 796.9 were used as the water quality boundary conditions. Interpolations were conducted to estimate unmeasured parameters on some dates. The conversions described in Section 3.4.2 were used to obtain estimates of ISS, LDOM, RDOM, LPOM, and RPOM.

3.4.4 Lateral Conditions

In addition to the UVR, Pool 3, and Pool 4, various unmonitored tributaries contribute flow, nutrients, and suspended solids to the LVR. A SWAT model was developed to estimate the runoff and the loadings from these areas and a detailed description of the SWAT model is provided in Appendix B and a summary is provided here.

SWAT modeled flow and loadings were set as 120 discrete inputs into the LVR W2 model. For subbasins 2 to 16, flows were directly specified to corresponding W2 segments. Flows from subbasins 17 and 20 to 28 were distributed to W2 segments based on segment length and the total LVR length within every subbasin. Some subbasins receive flows from both creek and overland flow. In such circumstances, flows from different subbasins were added together to create the W2 flow time series file. Correspondingly, concentrations of water quality parameters for such segments were flow-averaged. For other segments, SWAT modeled concentrations were directly used. SWAT outputs suspended solids, organic nitrogen, organic phosphorus, NO2, NO3, NH4, and mineral phosphorus. Mineral phosphorus was assigned to PO4 directly. Organic nitrogen was used to estimate the total organic matter and then distributed to LDOM, RDOM, LPOM, and RPOM. Algae biomass in the SWAT modeled flows were set to 0 and DO was set to 10 mg/L.

3.5 Weather Conditions

Weather data are required in W2 for water temperature simulation. In addition, the solar radiation data are critical for modeling algae. Direct precipitation and evaporation are important to achieve water balance in reservoirs and lakes with large surface area. The surface area of LVR is small compared to the drainage area. In addition, LVR is strongly impacted by Pool 3 and Pool 4. Therefore, the contribution of direct precipitation and evaporation are minimal. However, these data are still required to run the W2 model. The weather data for the W2 model include air temperature, dew point temperature, wind speed, wind direction, cloud cover, and solar radiation. The weather data are from the same stations using during the SWAT simulation, which are referenced in Appendix B.

3.6 Code Modification

Slight modifications to the W2 code were made to calculate total phosphorus. In the original W2 code, sediment associated phosphorus was calculated with two parts, sediment associated ortho-phosphate and other phosphorus. The second part of sediment associated phosphorus was computed directly by multiplying the specified partition coefficient with suspended sediment concentration. This algorithm is problematic since a partition coefficient should not directly be used as a ratio. To address this shortcoming, the W2 manual suggests turning off the partition calculation. However, sediment association of ortho-phosphate is a well-known phenomenon and the settling loss of ortho-phosphate is a major sink. Therefore, the code within the LVR W2 model was modified to retain the sediment association of ortho-phosphate but the second part of sediment associated phosphorus was deleted and the code was re-compiled after modification.

4.0 MODEL CALIBRATION AND VALIDATION

A model can only be used for developing a TMDL after calibration. The LVR model calibration included two steps. The first step was to calibrate the hydrodynamic simulation which determines the flow and mixing coefficients for solute transport. After the hydrodynamics were calibrated, water quality calibration was conducted without any change of coefficients related to hydrodynamics simulation.

Traditionally, model development involves two steps to determine water quality kinetics, especially for steady-state models: calibration and validation. In such circumstances, the quantity of data should be similar for both the calibration and validation periods. However, data for the LVR are not evenly distributed throughout the entire simulation period. Furthermore, hydrodynamic data are not available at the same stations as water quality data and data at different stations cover different periods. For example, the TSS data at station VR002.0 are from 1995 to 1997 whereas the TSS data at station VM001.M are from 1998 to 2006.

For LVR, the twelve-year calibration period addresses all types of hydrologic conditions such as low flow periods and high flow periods. Traditional calibration and validation would require the simulation period to be divided into two periods or to select a shorter period of several years. However, this was not possible for the LVR modeling due to the timing of the model setup and the collection of the 2006 data. Therefore the calibration was performed for the period 1/1/1995 to 8/31/2006 and validation was performed for the period 9/1/2006 to 12/31/2006.

Visual examination of the comparison of model results with observed data was the main approach used during the LVR model calibration. The locations where these comparisons were made are listed below and shown in Figure 3:

- MS295: Lower Vermillion River at Highway 54
- MS296: Vermillion Slough at E 4 Bridge
- MS297: Lower Vermillion River 5 miles southeast of Hastings
- MS298: Truedale Slough
- MS299: Lower Vermillion River at Highway 68 Bridge
- VR002.0: Lower Vermillion River at river mile 2
- VM00.1M: Vermillion River at Mouth

Statistics comparing model results and observed data were not calculated because matching the timing of the various factors affecting such statistics is critical and difficult to do in the LVR. For example, LVR is a highly dynamic system impacted by various factors such as individual storms and conditions in Mississippi River Pools 3 and 4. Water quality conditions (both observed and simulated) can therefore change dramatically in short periods of time. Because the model outputs data a fixed 12 hour time step and the observed data are collected at various times during the day, it is very difficult to make a direct comparison between the two data. In addition, with the daily boundary conditions and mixing assumption of each model cell, local phenomena are filtered out in the model. Based on these factors it was determined that making a visual comparison of the time series of model results against observed data was appropriate for ensuring reasonable trends, magnitudes, and response to external conditions of affecting the LVR. The final parameters used to obtain the model calibration are shown in Table 2, along with the W2 default values. The major values adjusted during the calibration process were the suspended solids settling rate, the phosphorus partition coefficient, and the parameters related to algae growth. The estimates of loads from the SWAT modeling of the local tributaries were also adjusted from the initial model runs to eliminate significant over-simulations of TSS concentrations for certain short-term periods.

Table 2. CE-QUAL-W2 parameter values for LVR model calibration.

Parameter	Value	Unit	W2 Default	Description
SSS	0.2	m day^{-1}	1	Suspended solids settling rate
EXH2O	0.25	m^{-1}	0.25 - 0.45	Extinction for pure water
BETA	0.45	-	0.45	Fraction of incident solar radiation absorbed at the water surface
EXA	0.1	m^{-1} /gm^{-3}	0.2	Algal light extinction
AG	1.8	day^{-1}	2	Maximum algal growth rate
AR	0.04	day^{-1}	0.04	Maximum algal respiration rate
AE	0.04	day^{-1}	0.04	Maximum algal excretion rate
AM	0.09	day^{-1}	0.1	Maximum algal mortality rate
AS	0.1	m day^{-1}	0.1	Algal settling rate
AHSP	0.003	g m^{-3}	0.003	Algal half-saturation for phosphorus limited growth
AHSN	0.014	g m^{-3}	0.014	Algal half-saturation for nitrogen limited growth
ASAT	75	W m^{-2}	75	Light saturation intensity at maximum photosynthetic rate
ALGP	0.005	-	0.005	Stoichiometric equivalent between algal biomass and phosphorus
ALGN	0.08	-	0.08	Stoichiometric equivalent between algal biomass and nitrogen
ALGC	0.45	-	0.45	Stoichiometric equivalent between algal biomass and carbon
ACHLA	145	-	145	Ratio between algal biomass and chlorophyll a
ALPOM	0.8	-	0.8	Fraction of algal biomass that is converted to particulate organic matter when algae die
ANPR	0.001	-	0.001	Algal half saturation constant for ammonium preference
PARTP	0.8	L mg^{-1}	-	Phosphorus partitioning coefficient for suspended solids

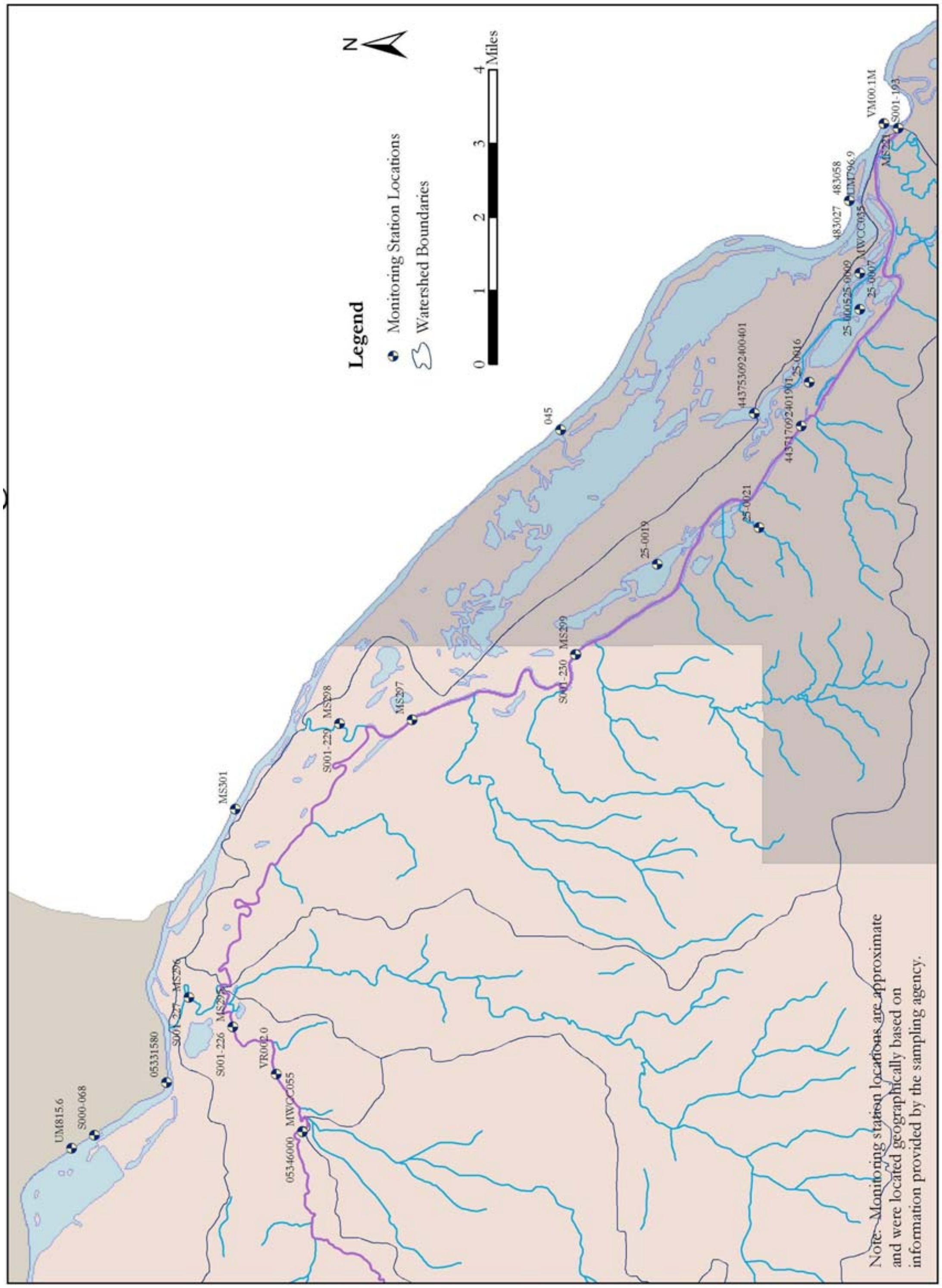


Figure 3. Calibration locations for the LVR W2 modeling effort.

4.1 Calibration and Validation Time Period

The calibration simulation period is from 1/1/1995 to 8/31/2006. Results for the period between 9/1/2006 and 12/31/2006 were used as a quasi-validation check on the model's performance (and are included with the calibration plots shown below). The model runs with a maximum time step of 60 seconds with W2 using an automatic time stepping function to determine the actual time step for each simulation period.

4.2 Hydrodynamics Calibration

The hydrodynamics calibration focuses on adjusting constants, parameters, and coefficients that are related to solving the free-surface governing equations. The hydrodynamics in LVR are greatly impacted by Pool 3 and Pool 4. The water from Pool 3 flows into LVR through dikes on the three sloughs. In the LVR W2 model, branches 2, 5, and 7 are the portions of the sloughs freely connected to Pool 3. Branches 3, 6, and 8 are the portions of the sloughs that are between LVR and the dikes. In addition, the Three Bridges Dike is on the main channel of LVR downstream of the confluence with Vermillion Slough. W2 provides a spillway/weir function to determine the flow rate over a dike based on elevations in the segments on both sides of the dike. The bottom elevations of the dikes were obtained from survey results. The actual bottoms of the dikes are not flat whereas W2 can only accept flat bottoms; therefore, the bottom dike elevations were adjusted slightly. The weir function parameters were also adjusted to obtain reasonable stage-discharge relationships for the dikes.

Water surface elevations measured at Etter Bridge and Vermillion Slough, and flow measured at Etter Bridge, were checked to adjust the dike bottom elevations and weir function parameters. In addition to the parameters related to the dikes, sensitivity of modeled flow and elevations to Manning's coefficients were tested during hydrodynamics calibration, but it was determined that Manning's coefficients do not have significant impact on the modeled flow and elevations. A comparison of simulated and observed elevations at Etter Bridge in 1998 is shown in Figure 4 and the 2006 comparison is shown in Figure 5. The comparison of simulated and observed elevations in Vermillion Slough in 2006 is shown in Figure 6 and the simulated and observed flow at Etter Bridge in 1998 is shown in Figure 7.

In addition to elevations and flows, water temperature was examined during the hydrodynamics calibration and it was determined that modeled water temperature agreed well with observed data using W2 default parameters for heat transport. The modeled data comparisons of temperature are shown in Figure 9 through Figure 11 for stations VM001.M, MS298, and MS296 respectively.

These figures show that the modeled elevations agree well with the observed data and the slight differences are attributed to specifications of the boundary conditions (e.g., measured elevations and input flows during storms). In addition, the W2 weir function appears to serve as an approximation for the dikes. The magnitudes, timing, and trends of the simulated elevations and flows agree well with the observed data, as does the simulated temperatures. Therefore the hydrodynamics simulation is considered calibrated and appropriate for simulating water quality.

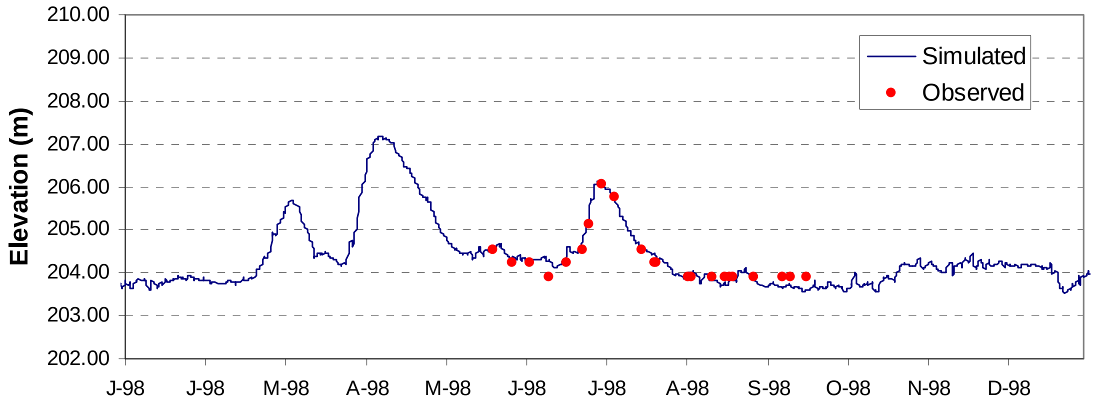


Figure 4. Simulated and observed elevations at Etter Bridge in 1998.

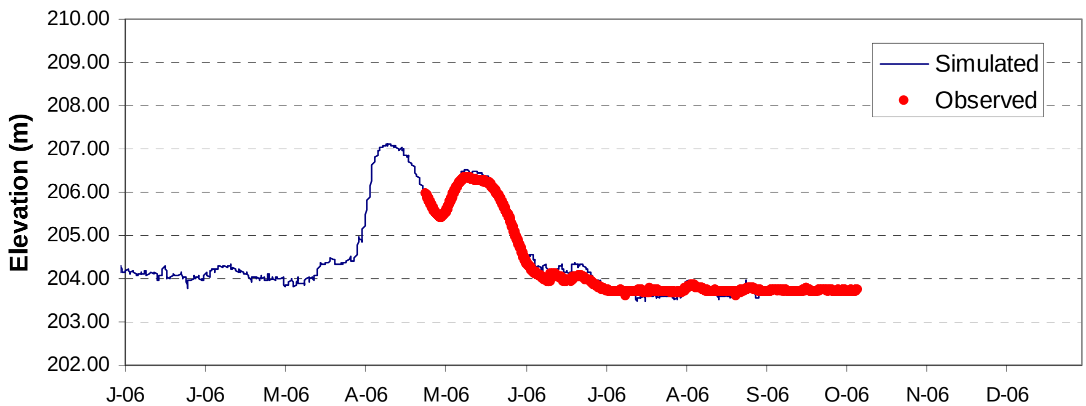


Figure 5. Simulated and observed elevations at Etter Bridge in 2006.

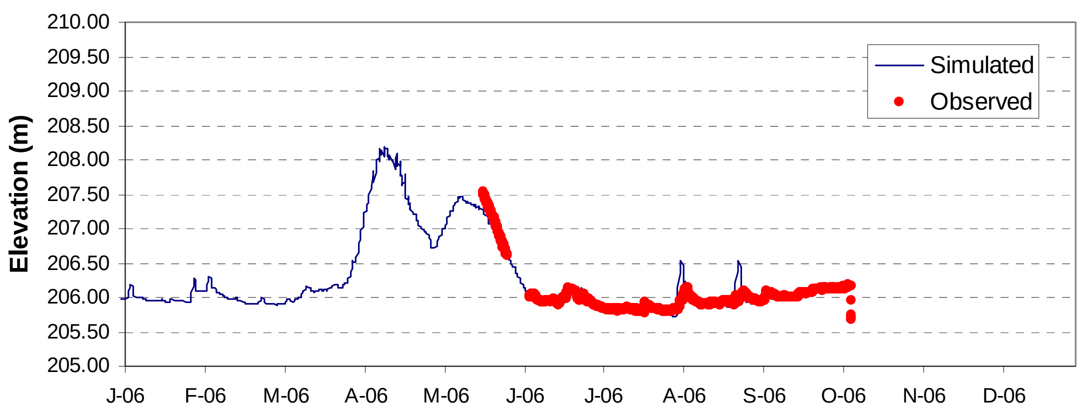


Figure 6. Simulated and observed elevations in Vermillion Slough in 2006.

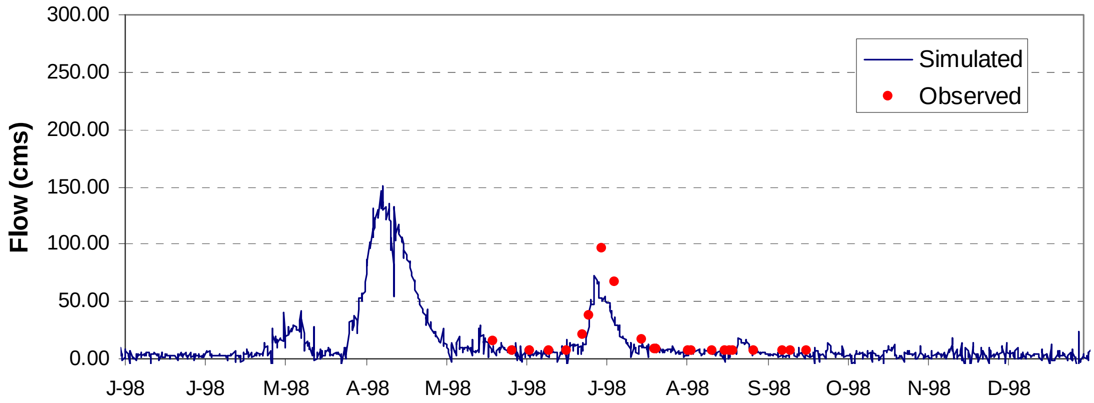


Figure 7. Simulated and observed flow at Etter Bridge in 1998.

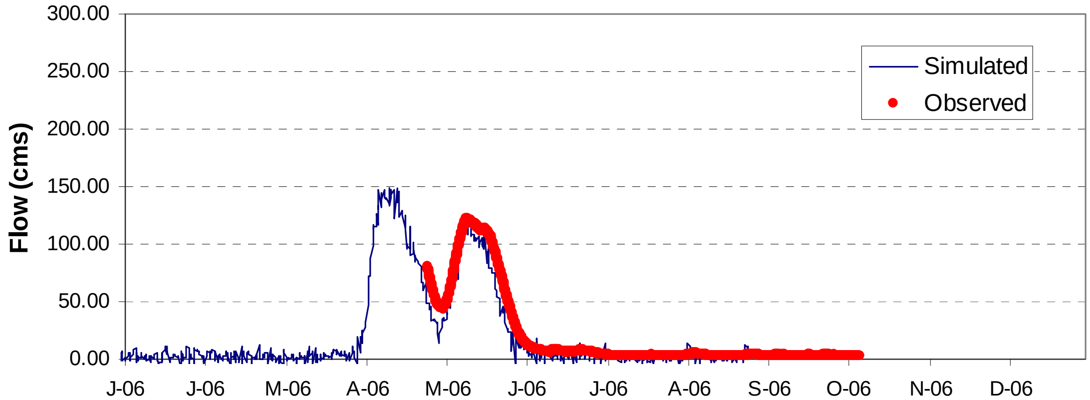


Figure 8. Simulated and observed flow at Etter Bridge in 2006.

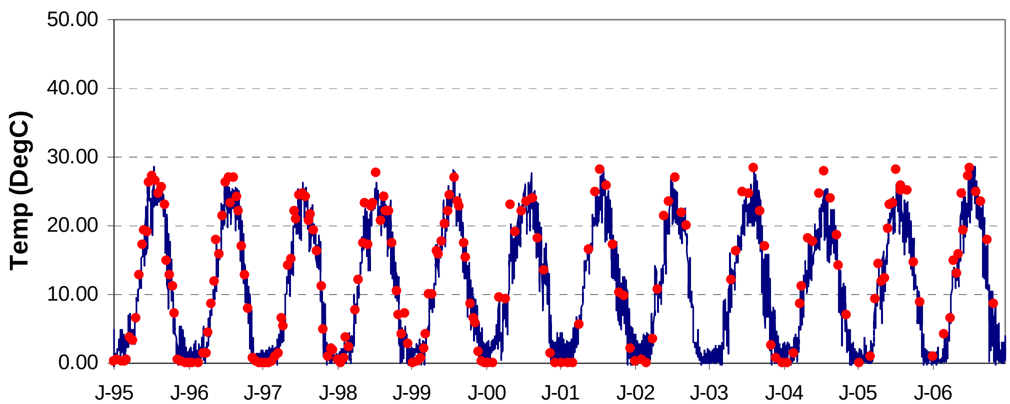


Figure 9. Simulated and observed water temperature at VM001.M

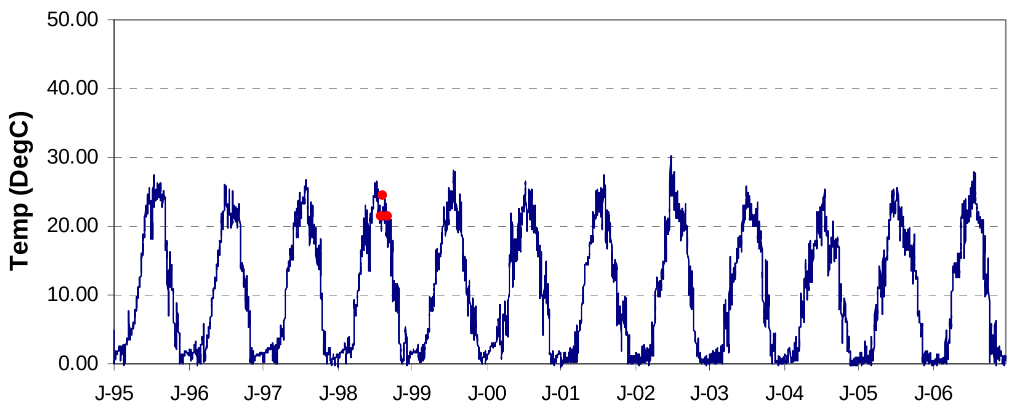


Figure 10. Simulated and observed water temperature at MS298 (Seg 104).

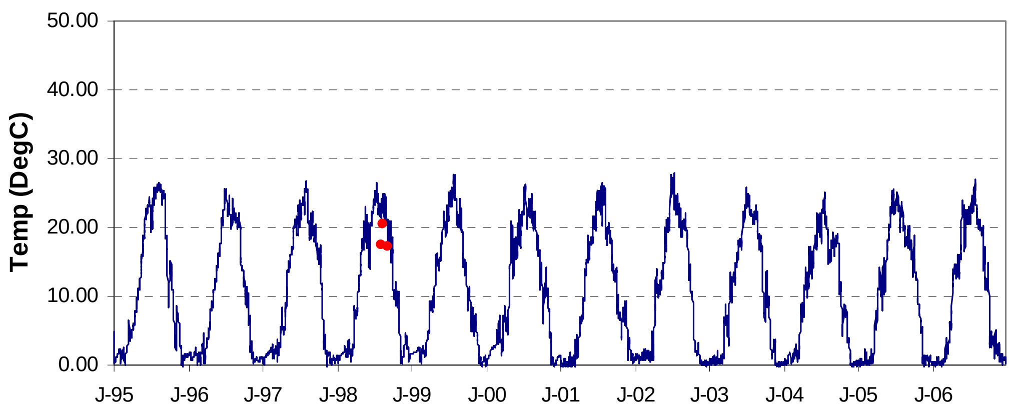


Figure 11. Simulated and observed water temperature at MS296 (Seg 20).

4.3 Calibration of Total Suspended Solids

Suspended solids calibrations were conducted for the entire simulation period. Total suspended solids include two components: ISS and TVS. The TVS results are estimated from the simulation of chlorophyll *a*. ISS is primarily affected by watershed loadings and boundary concentrations in Pool 3 and Pool 4. In addition to advection and diffusion, ISS may be transported vertically with settling and re-suspension. W2 provides a simple algorithm for settling and re-suspension (but without bed load computation) and, since very limited data are available and the W2 sediment re-suspension algorithm is over-simplified, re-suspension was turned off. Instead, the settling rate was considered a net settling rate (i.e., including both re-suspension and settling) and was adjusted until a reasonable agreement between simulated and observed data was obtained. With this approach it is therefore not possible to separate out a separate sediment load due to re-suspension. However, the model output can be indirectly used to obtain a qualitative estimate of the importance of re-suspension (e.g., by evaluating flow velocities or running the model with typical or default deposition rates and then interpreting the difference between deposition in that run and net deposition in the calibrated model as an estimate of the re-suspension flux).

The available monitoring data are for TSS and the W2 model simulated ISS. However, the main contribution of TSS is ISS. The results of ISS were converted to TSS using modeled algae results from the eutrophication simulation and the results are shown in Figure 12 through Figure 17. Results for more discrete two-year periods for station VM001.M are shown in Appendix C.

The results indicate that the model captured the magnitude and seasonal trend in TSS with the model results during dry weather conditions agreeing well with observed data. During storm events, the model generates higher TSS values due to upstream and lateral sediment loadings and, in general, the model results reveal that TSS in the LVR are strongly impacted by watershed loading.

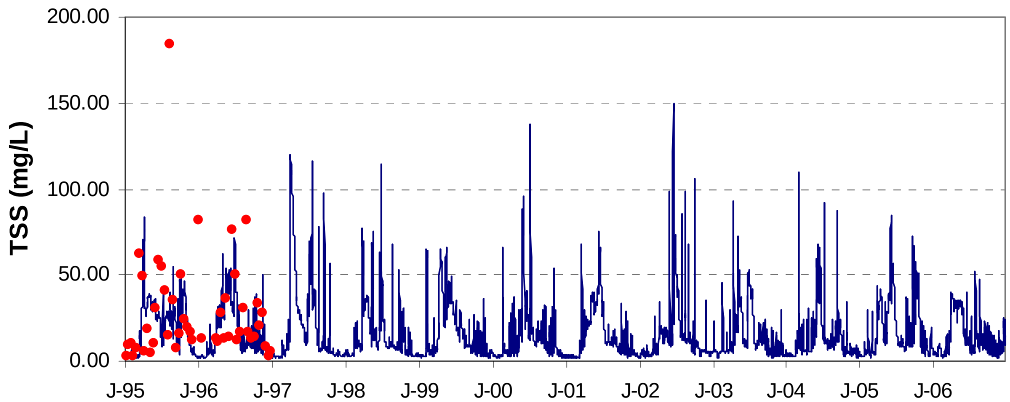


Figure 12. Simulated and observed TSS at station VR002.0.

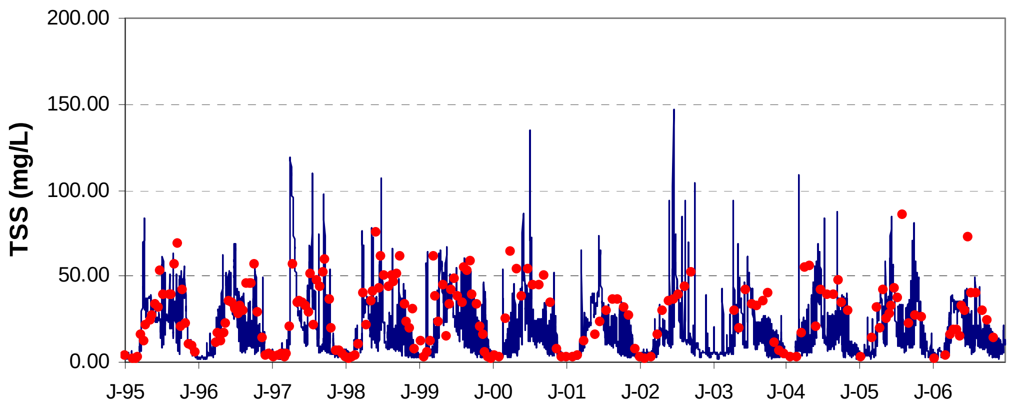


Figure 13. Simulated and observed TSS at station VM001.M.

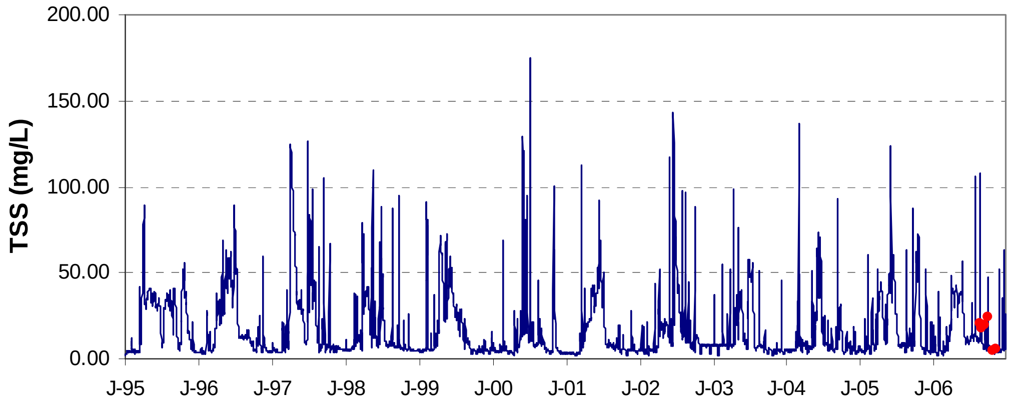


Figure 14. Simulated and observed TSS at station MS299.

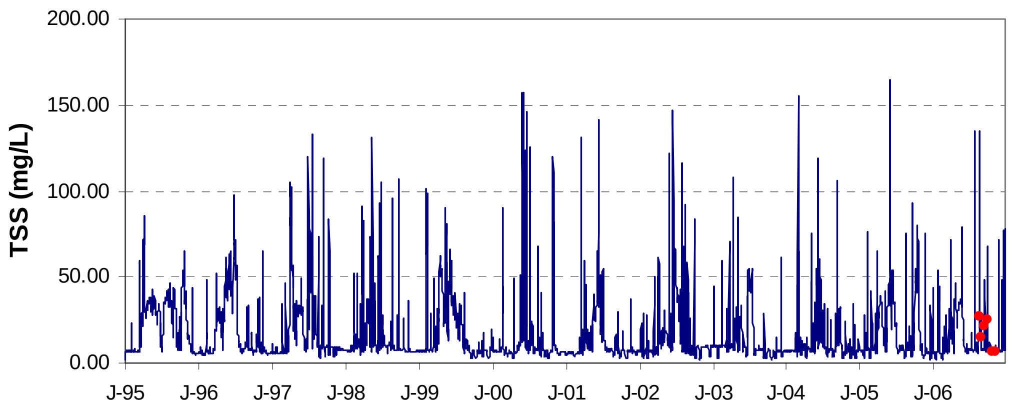


Figure 15. Simulated and observed TSS at station MS297.

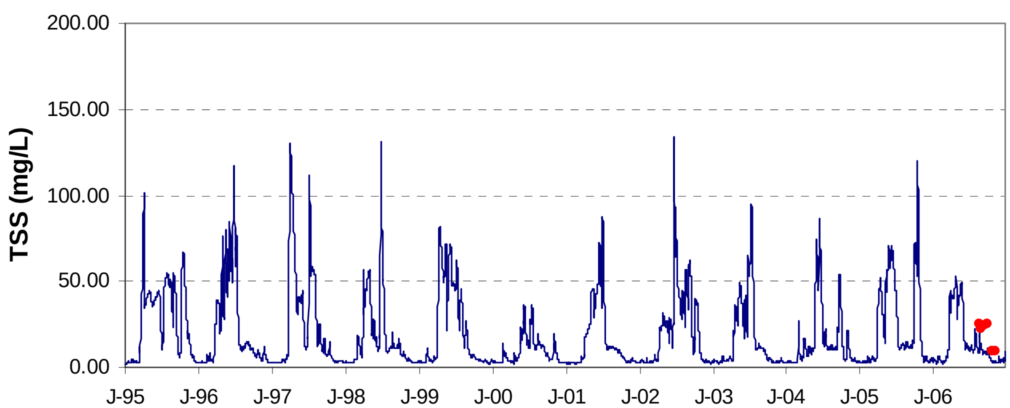


Figure 16. Simulated and observed TSS at station MS298.

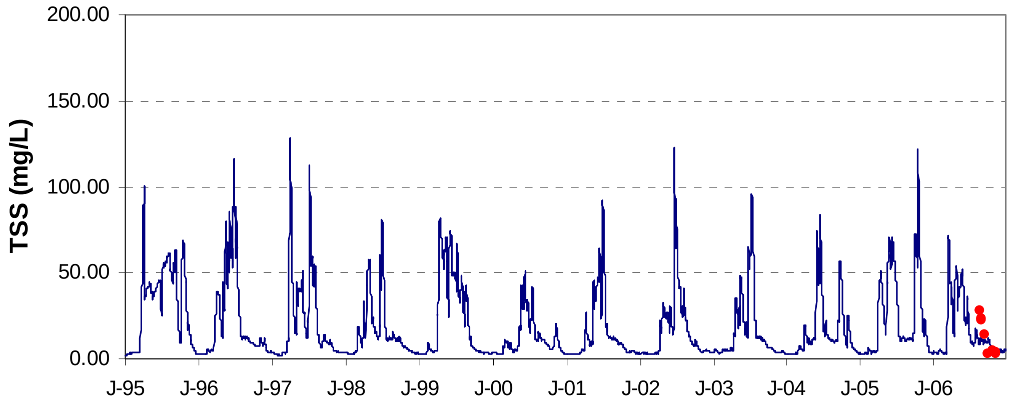


Figure 17. Simulated and observed TSS at station MS296.

4.4 Calibration of Algae

After the hydrodynamics were calibrated, the transport of nutrients and algae in LVR was determined by assigning constants and coefficients related to algae growth, excretion, mortality, and settling, as well as nutrient kinetics. Water temperature, solar radiation, and nutrients are all potential limiting factors for algae. In the initial stage of model development, default values of W2 constants and parameters were used. These values were then adjusted based on the differences between model results and observed data. In addition to the results for algae, nutrient and DO results were examined as supplemental indicators of the algal simulation. Since most of the available data are at station VM001.M, the calibration focused on VM001.M. Data from other stations were used for additional evaluation of model performance.

The simulated and observed data for TP, TP04, TN, NH4, NO3, and DO are shown in Figure 18 through Figure 48. The modeled algae results show that the model captured the main seasonal trends, although individual discrepancies exist. These may be due to several factors including: data collection methods, model assumptions, or accuracy in the boundary condition specifications. For example, data at station VM001.M indicate that algae levels in late 1998 and early 1999 were high despite temperatures being low. However, this relationship is not observed in the 1999 to 2002 data, suggesting that it might be due to local conditions that are difficult for the model to simulate.

The modeled TP and PO4 agree well with the observed data. The TP and PO4 levels depend not only on algae growth, but also the watershed loadings. The model generated peak values of TP and PO4 associated with storm events, with simulated nitrogen showing a similar pattern. However, the seasonal variations of NH4 are stronger than NO3. The modeled TN, NH4, and NO3 agree well with the observed data.

The simulated DO concentrations are slightly lower than the maximum observed DO and slightly higher than the minimum observed DO. However, the seasonal trends and diurnal variations were successfully reproduced with the model.

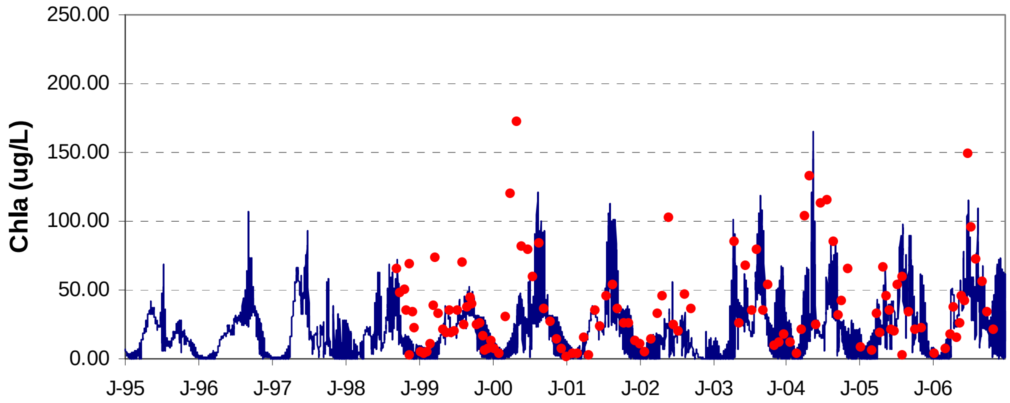


Figure 18. Simulated and observed algae at station VM001.M.

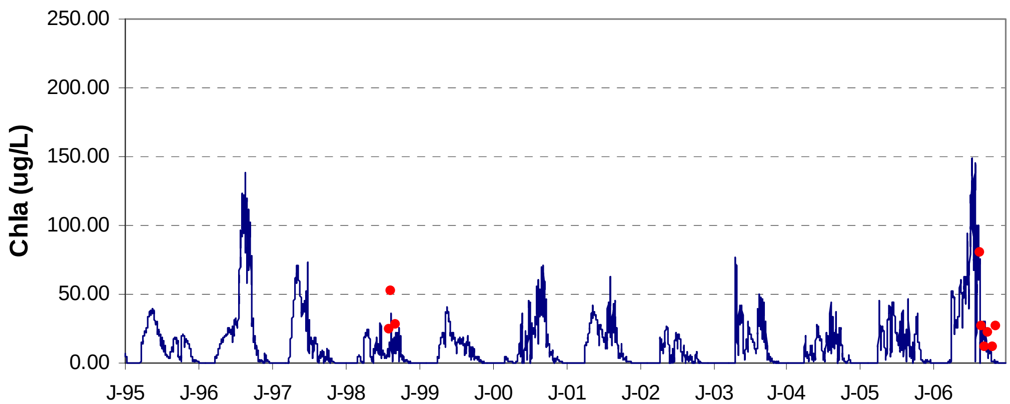


Figure 19. Simulated and observed algae at station MS299.

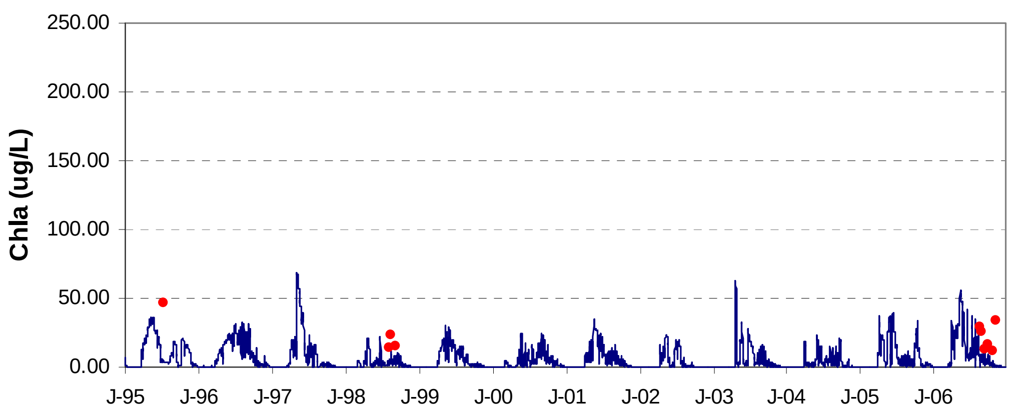


Figure 20. Simulated and observed algae at station MS297.

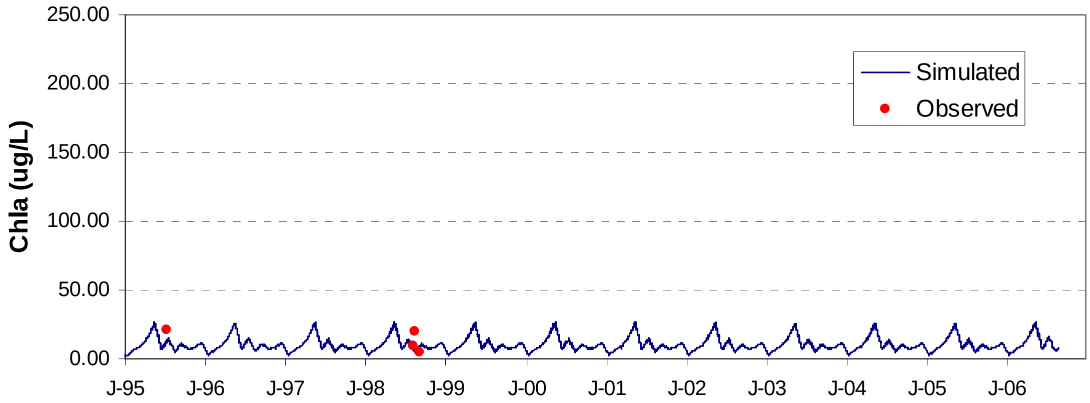


Figure 21. Simulated and observed algae at station MS295.

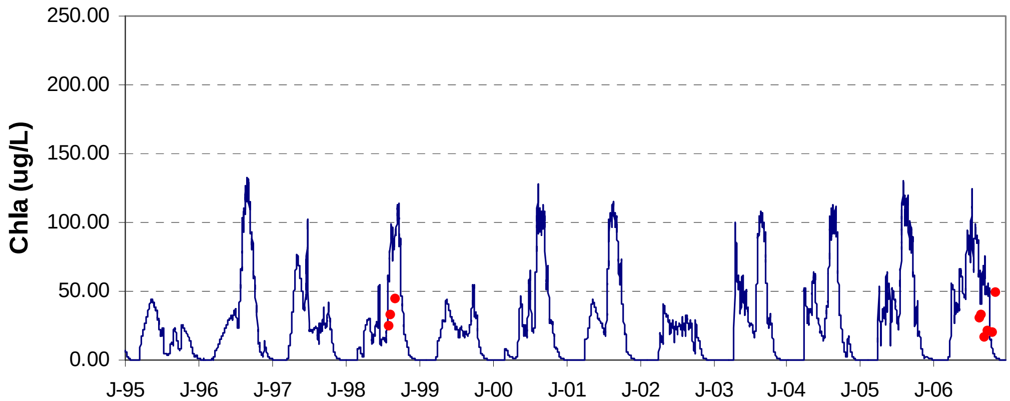


Figure 22. Simulated and observed algae at station MS298.

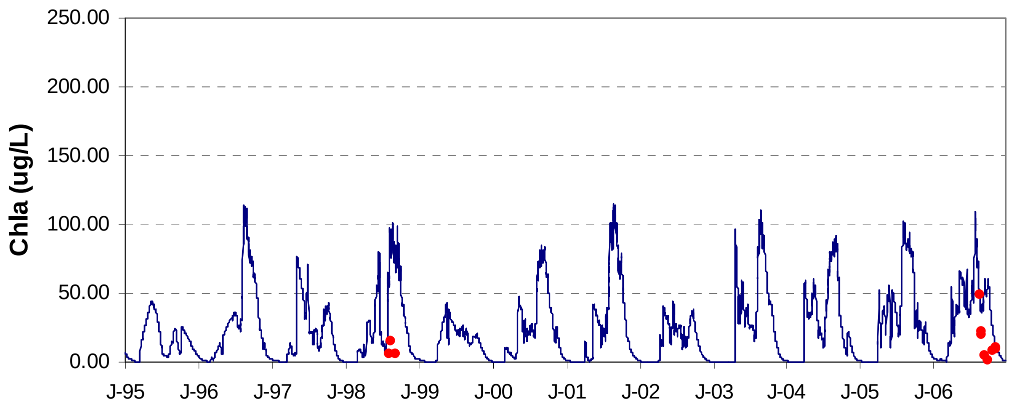


Figure 23. Simulated and observed algae at station MS296.

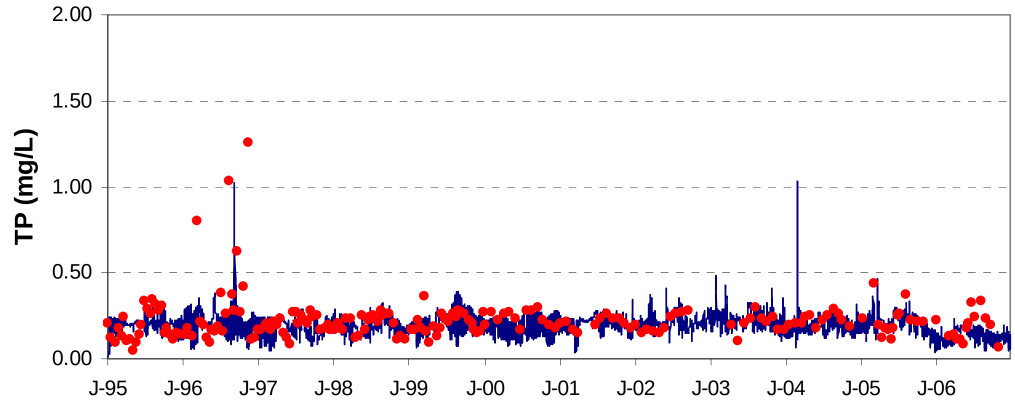


Figure 24. Simulated and observed TP at station VM001.M.

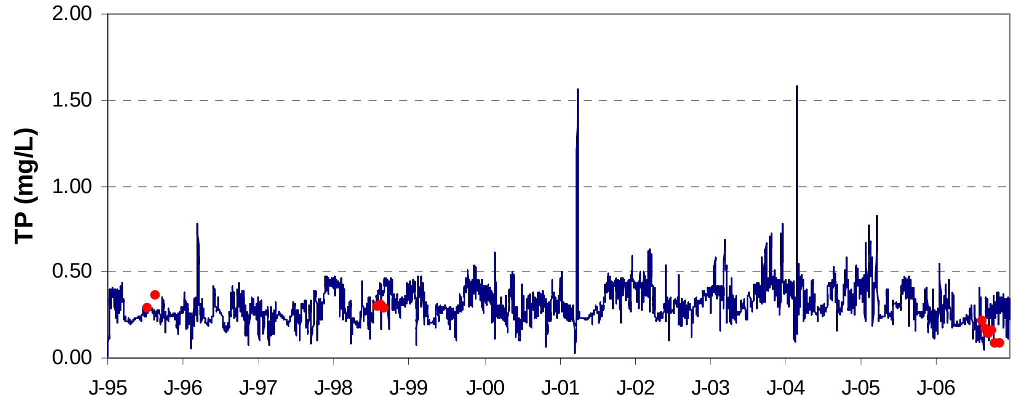


Figure 25. Simulated and observed TP at station MS299.

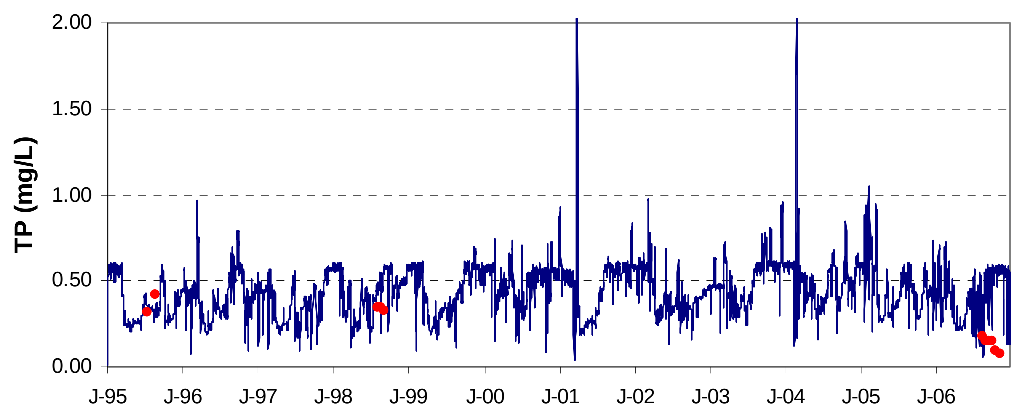


Figure 26. Simulated and observed TP at station MS297.

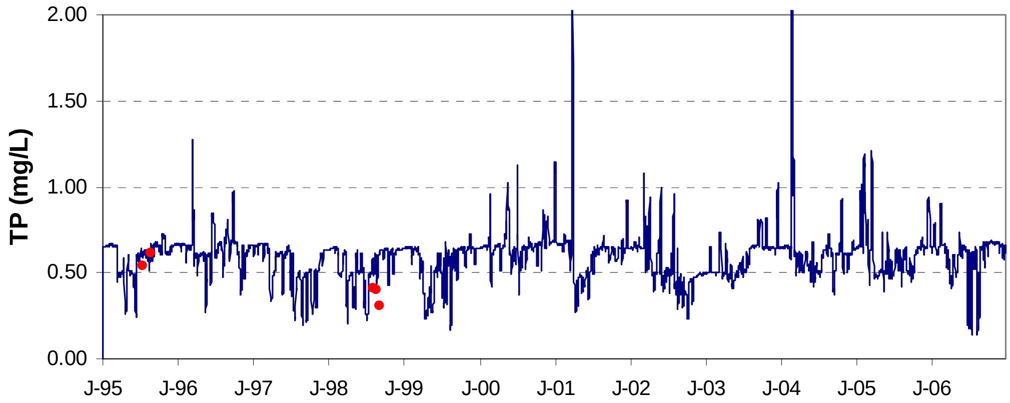


Figure 27. Simulated and observed TP at station MS295

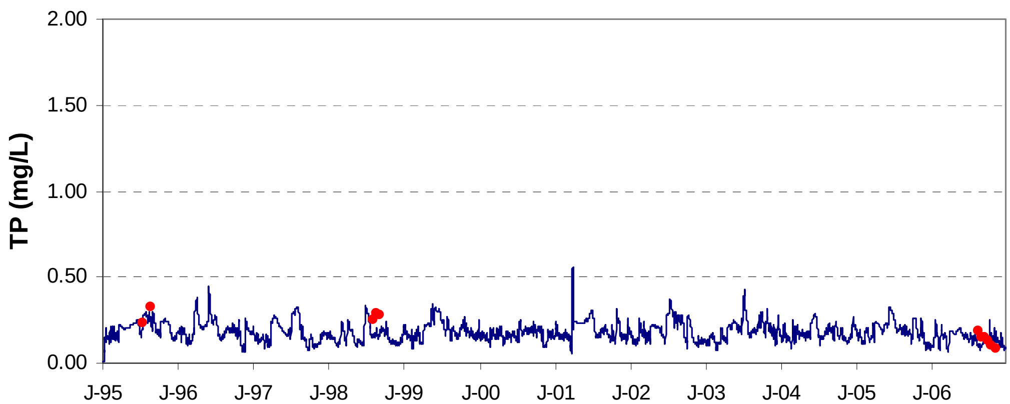


Figure 28. Simulated and observed TP at station MS298.

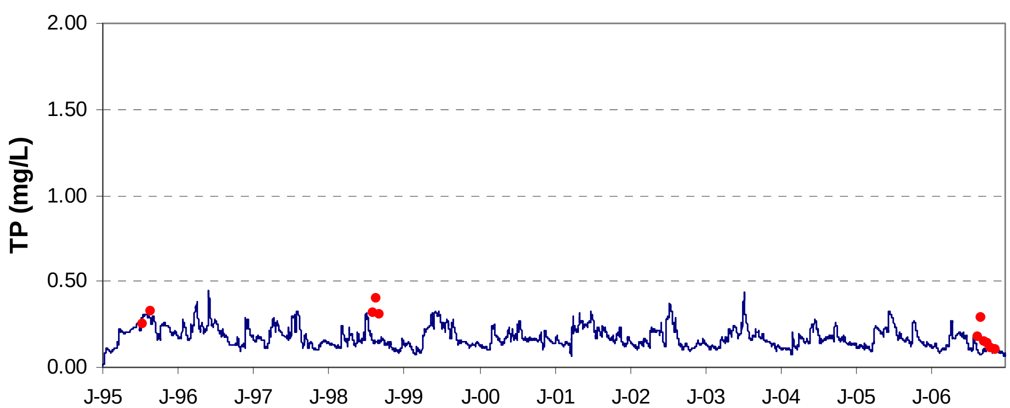


Figure 29. Simulated and observed TP at station MS296.

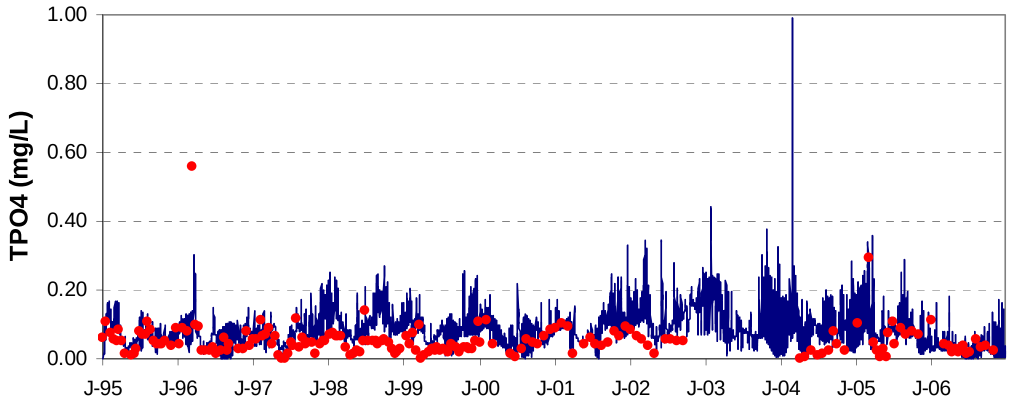


Figure 30. Simulated and observed TPO4 at station VM001.M.

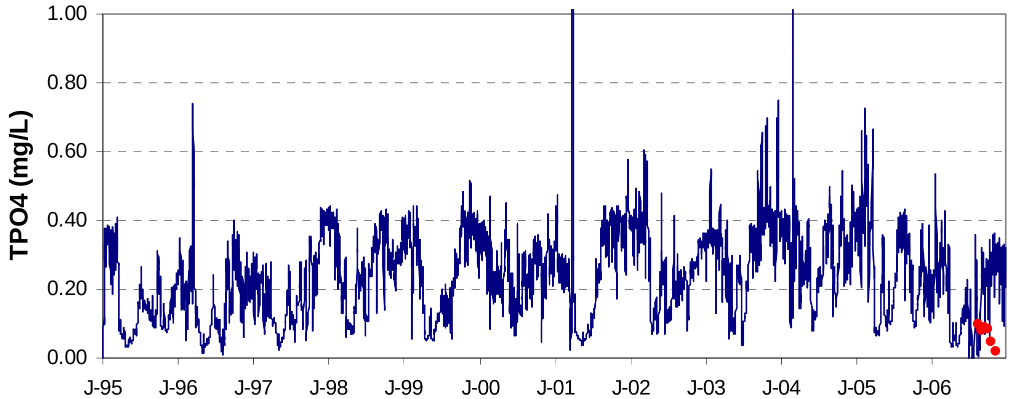


Figure 31. Simulated and observed TPO4 at stationMS299.

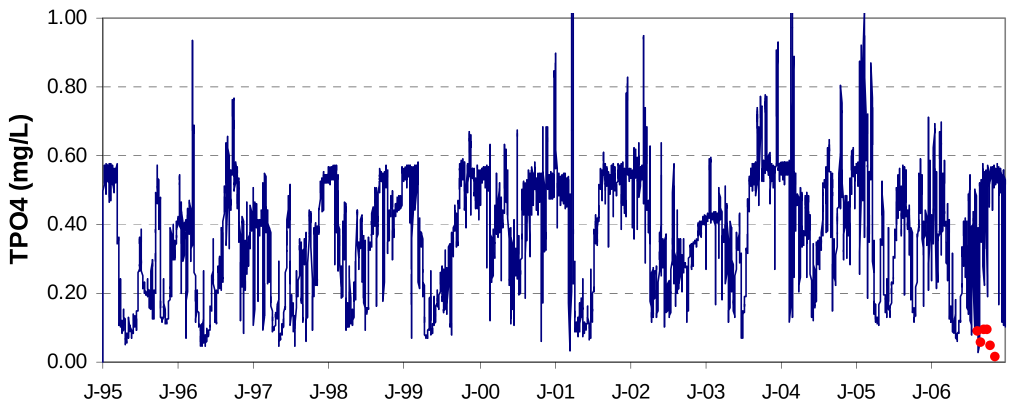


Figure 32. Simulated and observed TPO4 at stationMS297.

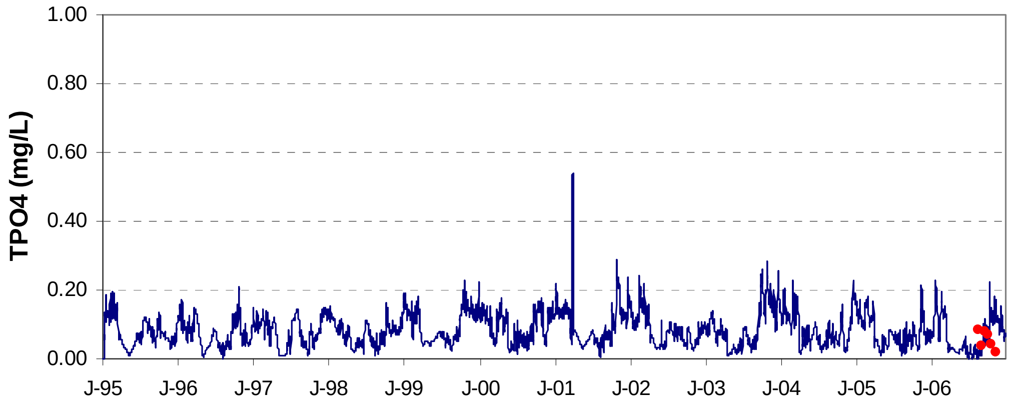


Figure 33. Simulated and observed TPO4 at station MS298.

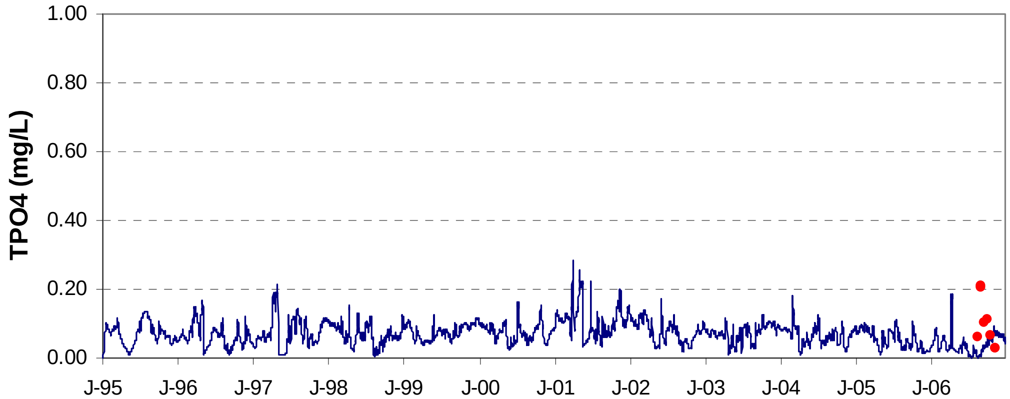


Figure 34. Simulated and observed TPO4 at station MS296.

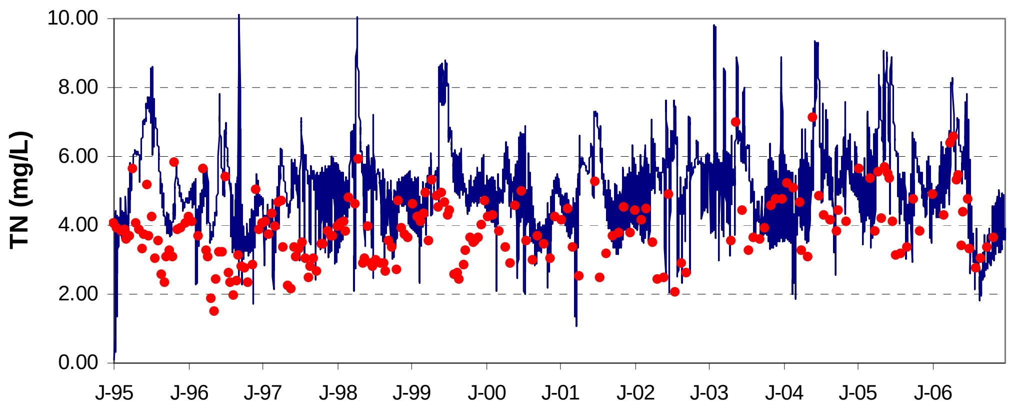


Figure 35. Simulated and observed TN at station VM001.M

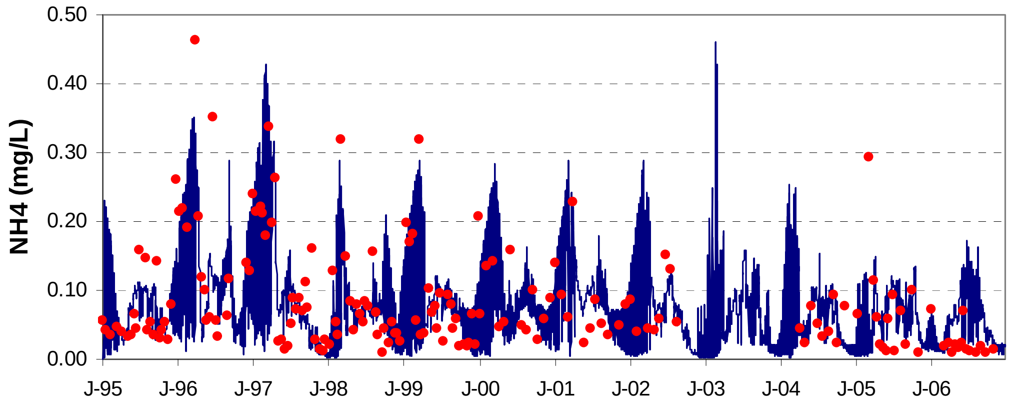


Figure 36. Simulated and observed NH4 at station VM001.M.

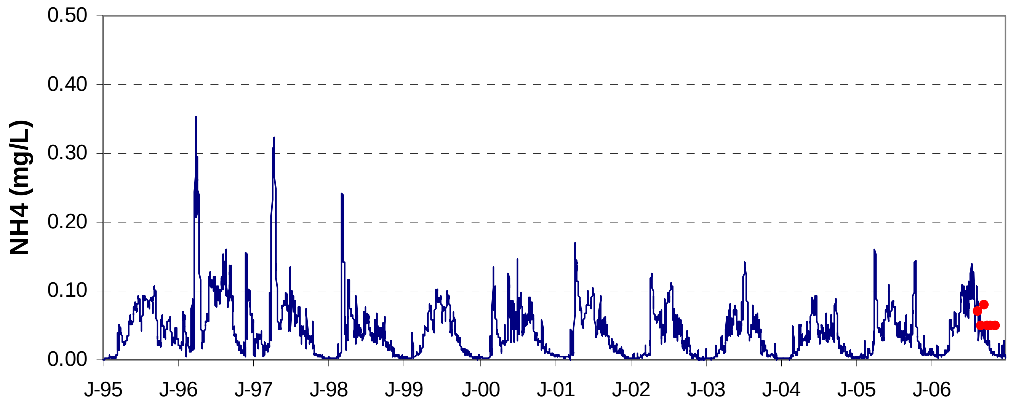


Figure 37. Simulated and observed NH4 at station MS299.

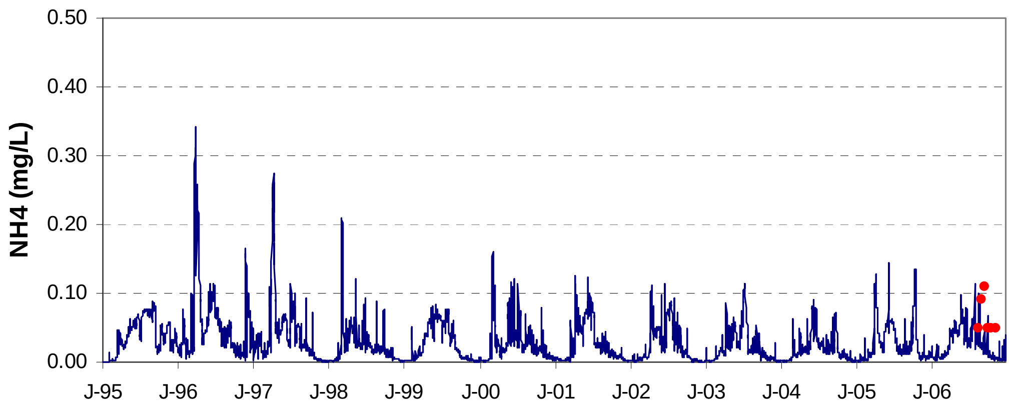


Figure 38. Simulated and observed NH4 at station MS297.

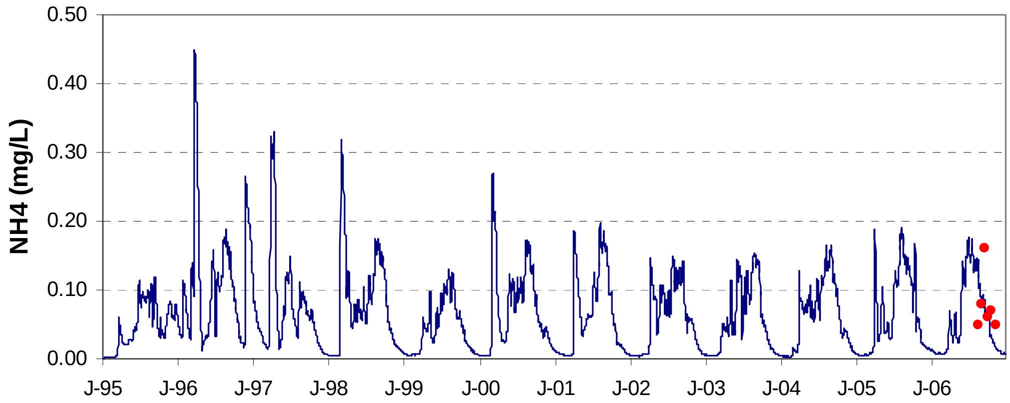


Figure 39. Simulated and observed NH4 at station MS298.

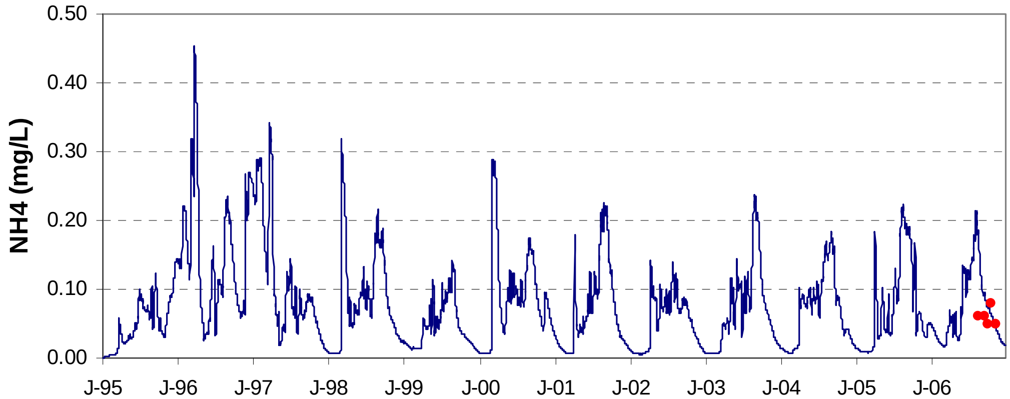


Figure 40. Simulated and observed NH4 at station MS296.

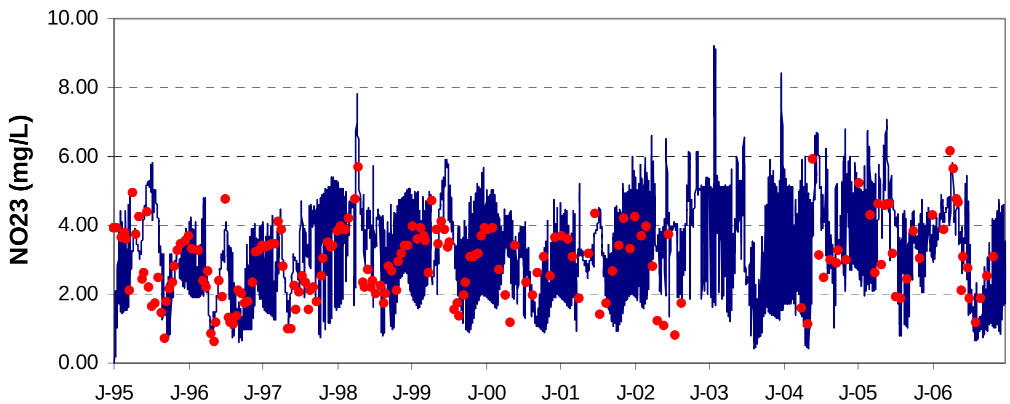


Figure 41. Simulated and observed NO23 at station VM001.M.

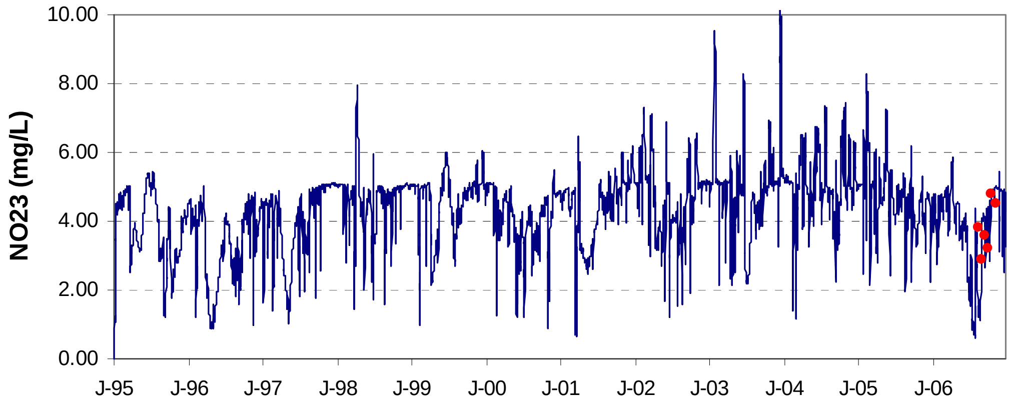


Figure 42. Simulated and observed NO23 at station MS299.

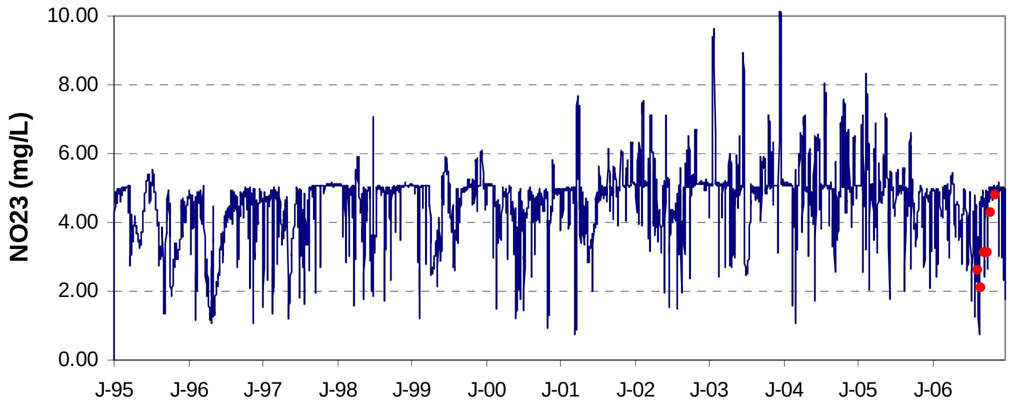


Figure 43. Simulated and observed NO23 at station MS297.

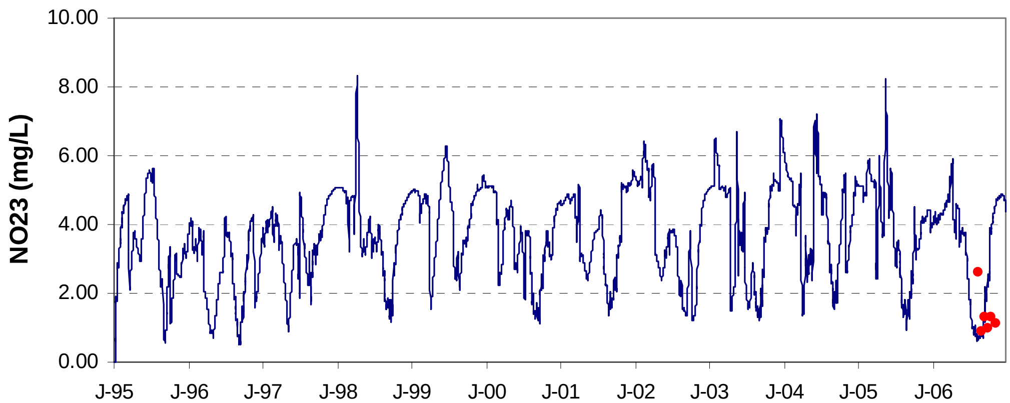


Figure 44. Simulated and observed NO23 at station MS298.

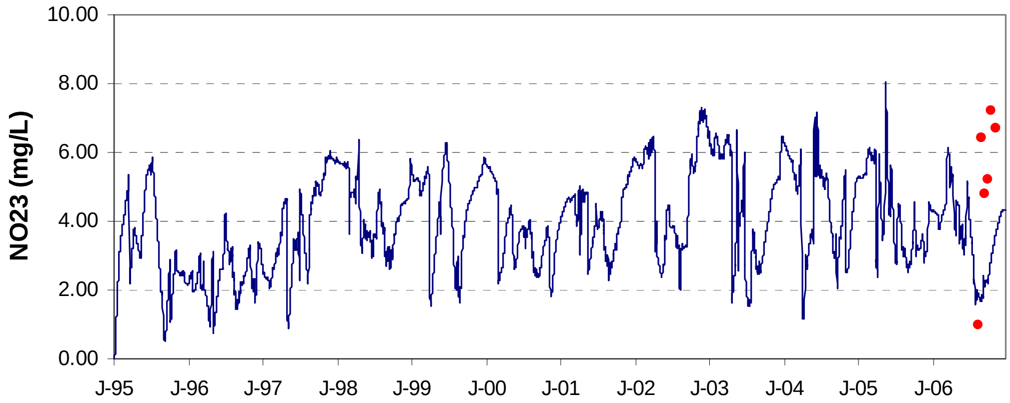


Figure 45. Simulated and observed NO23 at station MS296.

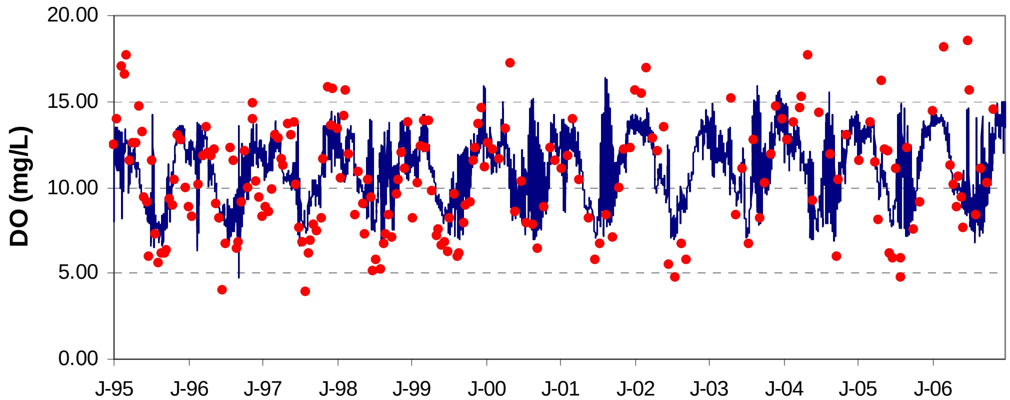


Figure 46. Simulated and observed DO at station VM001.M.

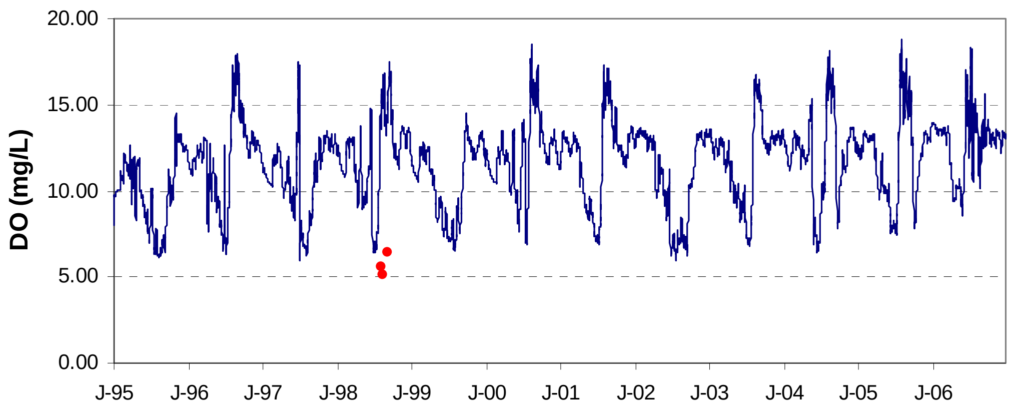


Figure 47. Simulated and observed DO at station MS298.

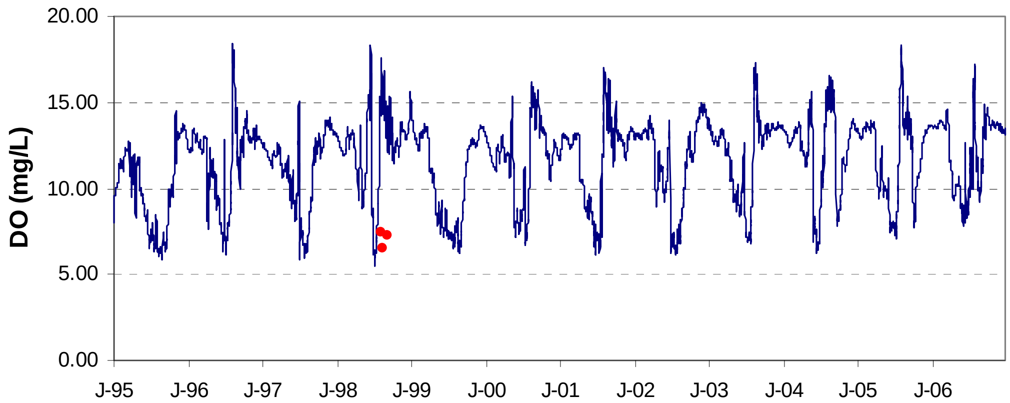


Figure 48. Simulated and observed DO at station MS296.

4.5 Turbidity Results

The W2 model does not directly simulate turbidity; instead, simulated turbidity was estimated based on the output for suspended solids using the following equation identified in the Phase I report (Tetra Tech, 2004):

$$\text{Turbidity} = -1.098 + \text{TSS}^{0.974}$$

The results from the original calibration are shown in Figure 49 through Figure 51 and indicate that the model does a good job of matching the temporal trends and event peak concentrations of turbidity at the downstream station VM00.1M (the only station with long-term sampling data). However, it is also evident that the model tends to underpredict turbidity in the period after the spring flood, particularly during non-event conditions. For the entire simulation the model tends to underpredict turbidity, with an average error of -1.7 and median error of -2.8 NTU.

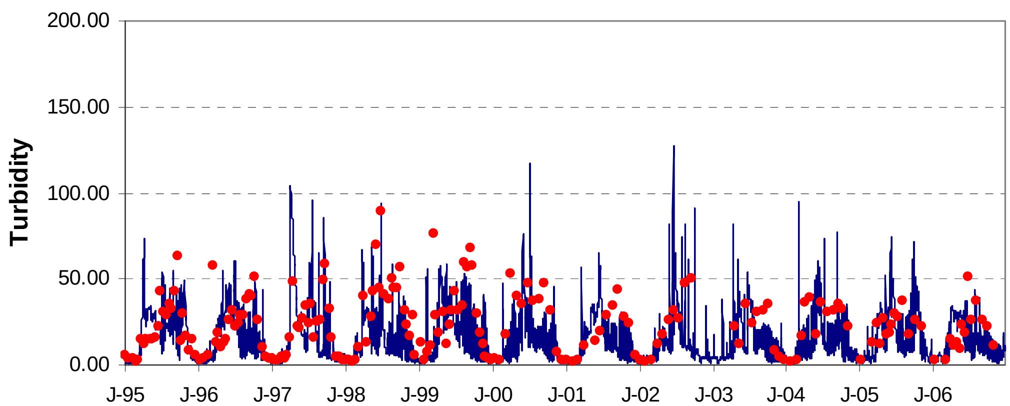


Figure 49. Simulated and observed turbidity at station VM001.M.

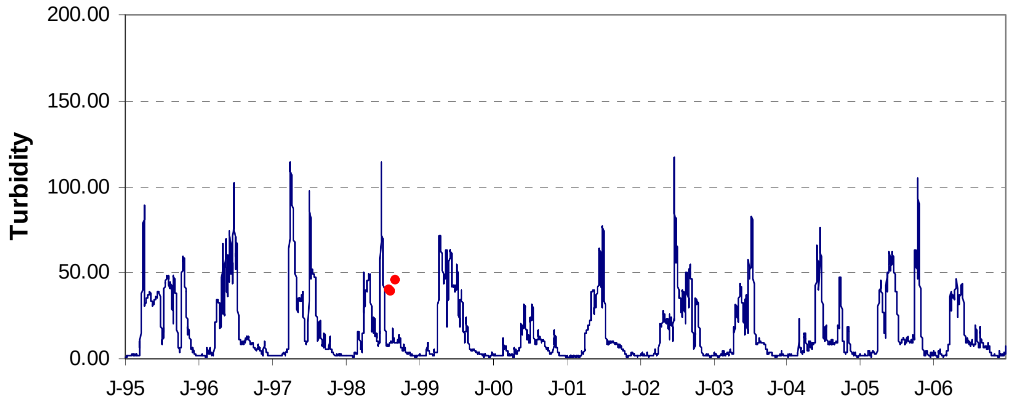


Figure 50. Simulated and observed turbidity at station MS298.

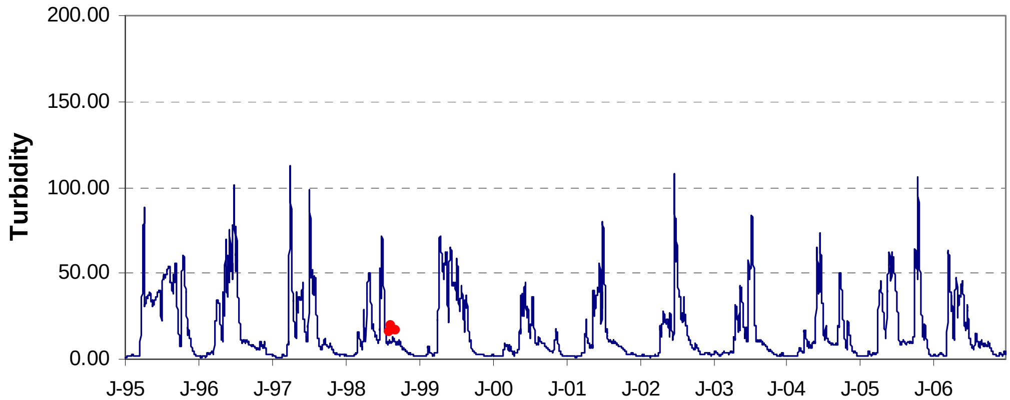


Figure 51. Simulated and observed turbidity at station MS296.

The key decision need of the model is to be able to accurately predict the excursions of the turbidity standard (greater than 25 NTU). Further analysis of the model's ability to predict criterion excursions was thus undertaken. Results were separated into two modes according to stage at the Prescott gage in Pool 3 of the Mississippi River and relative importance of Pool 3 intrusions into the Lower Vermillion. Mode 1 implies that Mississippi River inflows dominate conditions in the Lower Vermillion, while Mode 0 implies that significant inflow from the Mississippi does not dominate. When stage at Prescott is above about 676' there is strong inflow from Pool 3 into the Lower Vermillion (inflow begins at about 675.2', but does not exceed the normal flow from the Upper Vermillion until reaching about 676'), and days meeting this condition are designated as Mode 1. All other days are assigned Mode 0.

Under Mode 1 conditions (dominated by Pool 3 inflow) 42.2 percent of observations during the model run period at VM001.M are greater than 25 NTU. The model performs well under these conditions, predicting 43.7 percent of days greater than 25 NTU. This is not the case for Mode 0, where the model predicts only 7.7 percent excursions, whereas the data show 44.2 percent excursions.

Further examination of the model output versus the observed data reveals that the discrepancy is primarily due to low-to-moderate flow conditions following the spring flood and persisting into the fall. (In winter, both model and data show few values greater than 25 NTU). We conjectured that the spring flood stores highly turbid water in the vast wetland areas of the Lower Vermillion floodplain, and that this water gradually drains into the Lower Vermillion during the summer and fall, maintaining high turbidity under non-event conditions. Additionally, the solids load in these shallow areas may be replenished by wind-driven resuspension and other disturbances in the wetland areas.

Unfortunately, the phenomenon of storage and release of solids load in wetland areas and the impact of other disturbances is not readily handled in the W2 model. Therefore, the missing load component was handled in post-processing of the model. After some experimentation, it was determined that the missing load component is best represented by adding a fixed concentration of ISS to the system during the summer and fall. This provides a better match to observations than adding a fixed load. Use of a fixed concentration addition implies that the additional load varies with flow in the Lower Vermillion, which is consistent with the case in which discharge from wetland areas responds similarly to flow from the Upper Vermillion and local tributaries in response to precipitation events and changes in groundwater elevation over time.

The additional concentration was added under the following conditions:

- Flow mode = 0, implying no significant inflow from Mississippi Pool 3. (During Mode 1 conditions the model fits well, and the wetland areas are likely a net sink of ISS); and
- Months April through November, approximating the conditions under which the wetlands are not frozen over.

Through experimentation, it was determined that specifying the additional concentration at 22.3 mg/L ISS matched the observed percentage of turbidity greater than 25 NTU of 44.2 percent. The resulting turbidity time series is shown in Figure 52.

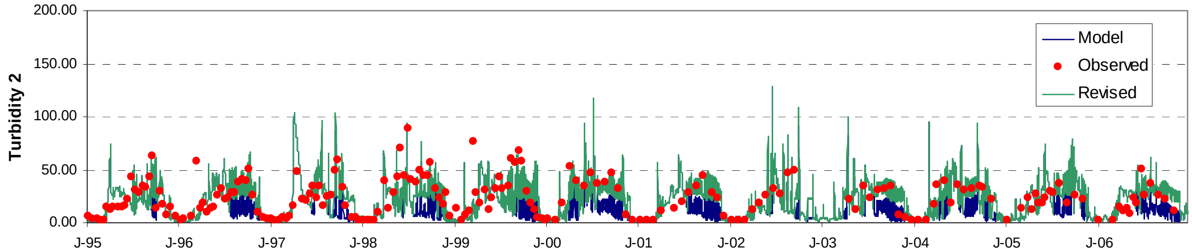


Figure 52. Comparison of Turbidity Predictions from CE-QUAL-W2 Model and Revised Predictions with added Load to Observed Turbidity at Station VM00.1M

5.0 SOURCE SUMMARY

The input and output data from the W2 modeling application were used to summarize the significant sources of flow and sediment into the LVR (Table 3). The results confirm the initial Phase I findings which suggested that, on a long-term basis, the LVR system appears to receive significantly more inflow from Mississippi Pool 3 than from the Upper Vermillion, the local tributaries, or Pool 4. However, during low to moderate flow conditions, inflow to the LVR can be dominated by its own watershed. The calibrated model can now be used to assess the potential impacts to turbidity in the LVR that might result from reducing the loads from each of these sources.

Table 3. Sources of flow and TSS to the LVR for the CE-QUAL-W2 modeling application, 1995 to 2006.

Source	Flow Volume		TSS Load		Method
	(m^3/yr)	Percent	(metric tons/yr)	Percent	
Upper Vermillion River	140,840,185	21.0%	2,298	7.8%	FLUX
Vermillion Slough	97,807,424	14.6%	4,852	16.5%	CE-QUAL-W2
Truedale Slough	208,303,719	31.0%	10,176	34.6%	CE-QUAL-W2
Carter Slough	140,770,856	21.0%	6,320	21.5%	CE-QUAL-W2
Local Tributaries	35,926,000	5.3%	4,791	16.3%	SWAT
Pool 4	9,516,025	1.4%	225	0.8%	CE-QUAL-W2
Internal Sources	38,598,768	5.7%	783	2.7%	Post-Processing
Total	671,762,977	100.0%	29,445	100.0%	

6.0 REFERENCES

Cole, T.M., and S. A. Wells. 2003. *CE-QUAL-W2: A two-dimensional, laterally averaged, Hydrodynamic. and Water Quality Model, Version 3.2*. Instruction Report EL-03-1, US Army Engineering and Research Development Center, Vicksburg, MS.

Tetra Tech. 2004. Lower Vermillion River Watershed Turbidity TMDL Project. Phase I Report: Data Gathering and Conceptual Model Development. Submitted to the Minnesota Pollution Control Agency By Tetra Tech, Inc. April 23, 2004.

APPENDIX A. FLUX ANALYSIS

A.1 FLUX Analyses

In the Phase I Report (Tetra Tech, 2004), the USACE FLUX program (Walker, 1987) was used to convert estimates of flow and concentration in the Vermillion River at Hastings into daily estimates of constituent load. At the time of the Phase I report, data were available to complete the FLUX analysis only through 2002. To support the Phase II modeling, the FLUX analyses have been updated and recalculated through the end of water year 2006.

MCES provided updated flow and water quality monitoring for the Vermillion River at Hastings. Approved data through 2004 were downloaded directly from the MCES Environmental Information Management System. Approved and quality assured data for 2005 along with provisional data for 2006 were provided directly by MCES (personal communication, Cassandra Champion, MCES, to Jonathan Butcher, Tetra Tech, October 2, 2006).

The revised FLUX models are summarized in Table A-1. Unlike the previous application, the model for total suspended solids (TSS) provides the best fit (lowest coefficient of variation) using the Regression-1 method, which relates the natural log of concentration to the natural log of flow within each stratum. All of the parameters were represented with a flow regression method (using either Regression-1 or Regression-3, a modification that applies the regression individually to each flow value combined with a back-transformation bias correction) to capture the relationships to flow present in the data. As was done previously, interpolated daily estimates are used for transmission to the W2 model, with the interpolation interval set to 14 days for TSS and 4 days for other parameters.

Table A-1. Revised FLUX Models for Vermillion River at Hastings

Parameter	Method	Stratification	Coefficient of Variation
Total Suspended Solids (TSS)	Regression-1	Mean Flow	0.083
5-Day Biochemical Oxygen Demand (BOD5)	Regression-3	None	0.094
Total Kjeldahl Nitrogen (TKN)	Regression-3	Month (2/15-4/15 separate)	0.044
NO_2+NO_3 (NOx)	Regression-1	None	0.030
Total Phosphorus (TP)	Regression-3	Mean Flow	0.033
Total Volatile Solids (TVS)	Regression-1	Mean Flow	0.067

Observed and predicted total phosphorus concentrations for the Vermillion River at Hastings are shown in Figure A-1.

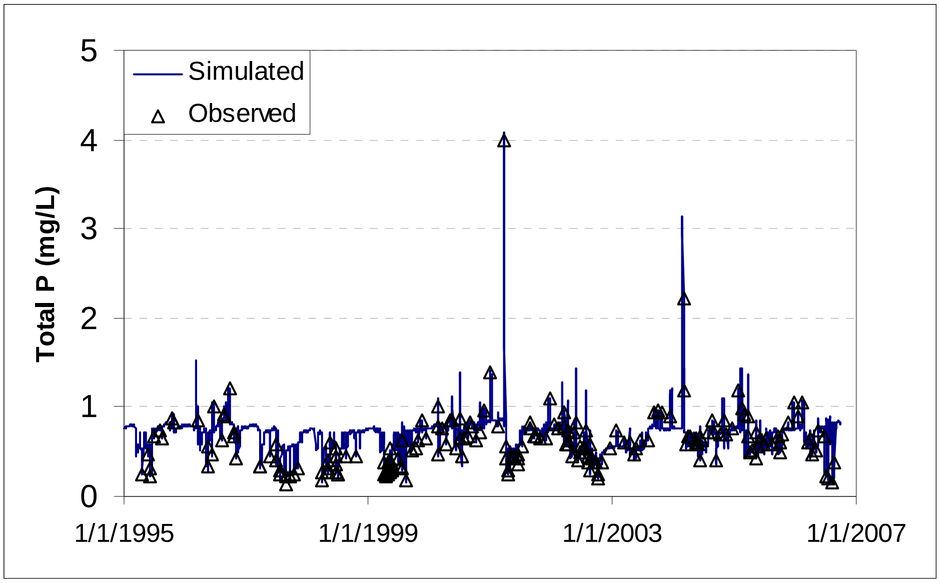


Figure A-1. Observed and FLUX-Interpolated Total Phosphorus Concentration, Vermillion River at Hastings

MCES also uses the FLUX approach to estimate loads at their water quality stations. We compared our estimates to MCES estimates (personal communication from Karen Jensen, MCES, to Jonathan Butcher, Tetra Tech, Jan. 29, 2007) for consistency. The MCES estimates were developed independently from those presented above, and in some cases use different solution methods (e.g., the IJC flow-weighted mean concentration method for Total P). MCES provided results for four parameters. Comparison (Table A-2) shows that the two estimates are very similar, less than 6 percent. Differences of this size are not statistically significant based on the coefficients of variation shown in Table A-1.

Table A-2. Comparison of Tetra Tech and MCES FLUX Estimates of Average Annual Load (kg/yr) for Vermillion River at Hastings, October 1994-September 2006

	Tetra Tech	MCES	Percent Difference
5-Day Biochemical Oxygen Demand (BOD5)	314,387	329,723	4.9%
NO_2+NO_3 (NOx)	714,035	736,439	3.1%
Total Kjeldahl Nitrogen (TKN)	146,728	151,723	3.4%
Total Phosphorus (TP)	83,706	79,077	-5.5%
TSS	4,659,233	N/A	N/A
TVS	1,469,551	N/A	N/A

Not all constituents required by the W2 model are regularly monitored at Hastings, and those constituents cannot be directly addressed through FLUX analyses. The following assumptions were made to complete the boundary data set:

- BOD5 was assumed to be representative of labile organic matter. Using standard values, labile carbon was assumed equivalent to BOD/1.68, and labile biomass equivalent to labile carbon times 2.0408.
- For refractory organic matter, we first assumed that ultimate carbonaceous BOD was 3.5 times BOD5. After subtracting out the labile fraction, refractory organic matter would be equal to 2.5 times labile organic matter.
- Ammonia nitrogen (NH_3-N) was not analyzed directly with FLUX because a large number of the observations are non-detect. Instead, NH_3-N was estimated from total Kjeldahl nitrogen. Because the ammonia fraction is expected to vary throughout the year, the conversion factor was assigned on a monthly basis based on observed ratios, ranging from a low of 0.076 percent in December to a maximum of 0.588 percent in March.
- Only limited data are available on the orthophosphate content of total phosphorus at this station. The median observed fraction of 0.85 was used for model input.

APPENDIX B. SWAT ANALYSIS

B.1 SWAT Model for Direct Drainage to the Lower Vermillion River

Boundary conditions for the Vermillion River at Hastings and the Mississippi River are based on monitored data. There are, however, additional land areas that drain to the Vermillion River downstream of Hastings. To address loadings from these areas, a SWAT watershed model (Neitsch et al., 2002) was developed for the Lower Vermillion River Watershed using the setup tools available with BASINS 3.1 and predefined watershed boundaries. Land use and soils were obtained from public agencies, as described below.

B.2 Subwatershed Boundaries

Subwatershed boundaries were refined to reflect input to differing segments of the CE-QUAL-W2 model. The starting point was provided by the Minnesota DNR Minor Watersheds polygon file. This was first clipped to cut off the portion of the watershed upstream of the ConAgra Dam in Hastings (upstream boundary of the W2 model). The resulting upland area was then subdivided into tributary drainages using the BASINS auto delineation tool (subwatersheds 2 to 17). The remaining area is primarily in the flat floodplain of the Mississippi and Vermillion River systems, where drainage divides are indistinct. This area was subdivided manually into additional subwatersheds (20 to 28) along different segments of the Lower Vermillion.

The subwatershed boundaries (Figure B-1) were added to a BASINS 3.1 project set up for the Lower Vermillion Watershed. The NHD stream coverage and digital elevation data acquired from the BASINS download page were used to calculate the subwatershed modeling parameters defined in Table B-1 and Table B-2.

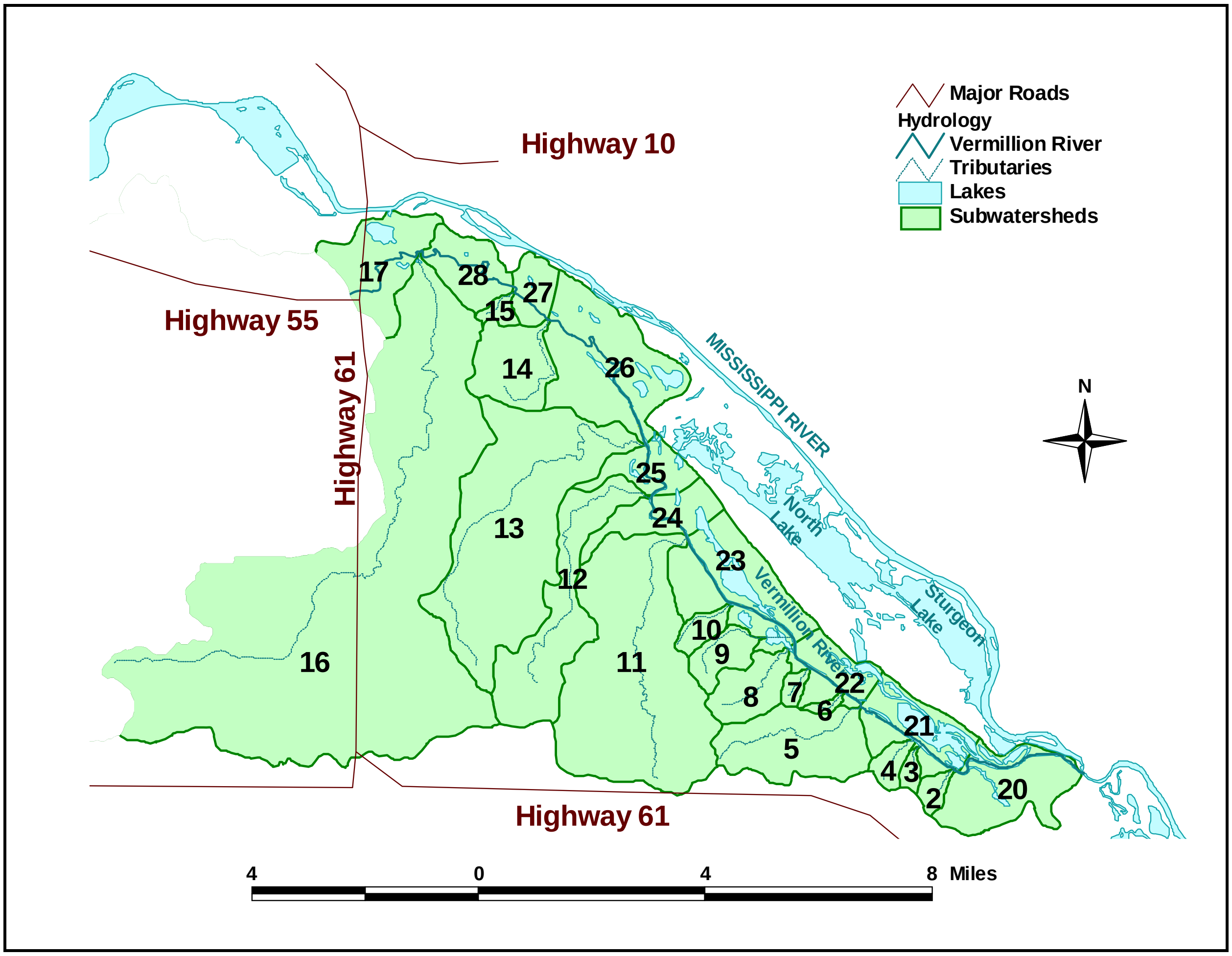


Figure B-1. Subwatersheds of the Lower Vermillion River Watershed

Table B-1. Definition of Watershed Parameters

Parameter Code	Description
Area	Subwatershed area (hectares)
Len1	Longest stream path in subwatershed (meter)
Slo1	Subwatershed slope (percent)
Sll	Field slope length (meters)
Csl	Slope of longest stream path in subwatershed (percent)
Wid1	Stream reach width (meters)
Dep1	Stream reach depth (meters)
Elev	Elevation of centroid of subwatershed (meters)

Table B-2. Subwatershed Parameters for the Lower Vermillion River Watershed

Subbasin	Area	Len1	Slo1	Sll	Csl	Wid1	Dep1	Elev
2	77.847	1211.916	6.743	60.976	7.839	0.975	0.108	297
3	54.176	1009.338	5.709	60.976	9.709	0.767	0.092	305
4	103.031	1592.147	5.186	60.976	6.281	1.346	0.134	304
5	758.775	5144.625	4.613	91.463	2.138	4.530	0.300	290
6	33.133	988.693	5.014	60.976	9.609	0.748	0.090	295
7	58.890	1110.904	5.014	60.976	8.012	0.748	0.090	295
8	328.916	3065.819	5.146	60.976	3.490	2.370	0.195	298
9	214.991	3504.258	6.364	60.976	2.625	1.900	0.168	299
10	117.959	2145.761	6.264	60.976	4.288	1.240	0.127	290
11	2376.983	9336.770	3.751	91.463	1.114	8.452	0.455	261
12	1002.149	8988.513	2.463	91.463	0.923	5.939	0.360	268
13	2280.052	12631.952	1.404	121.951	0.649	7.514	0.421	254
14	483.233	3995.831	0.524	121.951	1.176	2.165	0.184	259
15	68.251	1129.215	3.265	91.463	4.782	3.081	0.232	220
16	6830.467	21648.129	1.942	121.951	0.439	16.166	0.701	255
17	623.342	3350.342	2.149	91.463	0.776	2.475	0.201	221
20	708.324	30761.668	3.151	91.463	0.016	9.282	0.485	207
21	513.189	30761.668	3.151	91.463	0.016	9.282	0.485	207
22	351.342	30761.668	3.151	91.463	0.016	9.282	0.485	207
23	878.504	30761.668	3.151	91.463	0.016	9.282	0.485	207
24	362.877	30761.668	3.151	91.463	0.016	9.282	0.485	207
25	295.154	30761.668	3.151	91.463	0.016	9.282	0.485	207
26	1124.131	30761.668	3.151	91.463	0.016	9.282	0.485	207
27	210.653	30761.668	3.151	91.463	0.016	9.282	0.485	207
28	374.995	30761.668	3.151	91.463	0.016	9.282	0.485	207

B.3 Land Use/ Land Cover Data

Two datasets were acquired to develop the land use/ land cover input for the SWAT model setup: 1) a statewide land use/ land cover dataset and 2) a more detailed land cover dataset for Dakota County and a portion of Goodhue County. The statewide raster data classifies land use/ land cover with seven cover classes: urban, agriculture, grassland, forest, water, wetland and shrubland. This dataset also provides estimates of percent impervious coverage. The statewide data was developed from 2000 Landsat TM and

Landsat ETM+ satellite images by the University of Minnesota Remote Sensing and Geospatial Laboratory (http://www.land.umn.edu/index.htm)

The more detailed land cover classification is a polygon coverage that includes Dakota County and the Etter Creek Watershed in Goodhue County and represents land cover conditions during the years 2000 and 2001 with a minimum mapping unit of 1 acre. In conjunction with MN Department of Natural Resources (MN DNR) and Friends of the Mississippi River (FMR), the Dakota County Soil & Water Conservation District (SWCS) developed this coverage by using the Minnesota Land Cover Classification System (MLCCS) to interpret land cover types. After cross-comparison of the two coverages, it was determined that the statewide coverage was preferable to the purposes of the project as it gave similar resolution in the project area and covered the entire watershed.

Figure B-2 shows the eight SWAT land uses classes defined for the Lower Vermillion SWAT model. Modeling parameters for each class are described in Table B-3. The distribution of land use by model subbasin is summarized in Table B-4.

In addition to the seven classes identified in the land cover classification, a separate class for corn-soy rotation in mulch tillage was added to represent areas in which conservation tillage is practiced. Based on information received from Dakota Co. Soil and Water Conservation District (personal communication from Brad Miller, Dakota Co. SWCD to Kevin Kratt, Tetra Tech, September 25, 2006) approximately half of the row crop (corn-soy rotation) agriculture was assumed to be in conservation tillage.

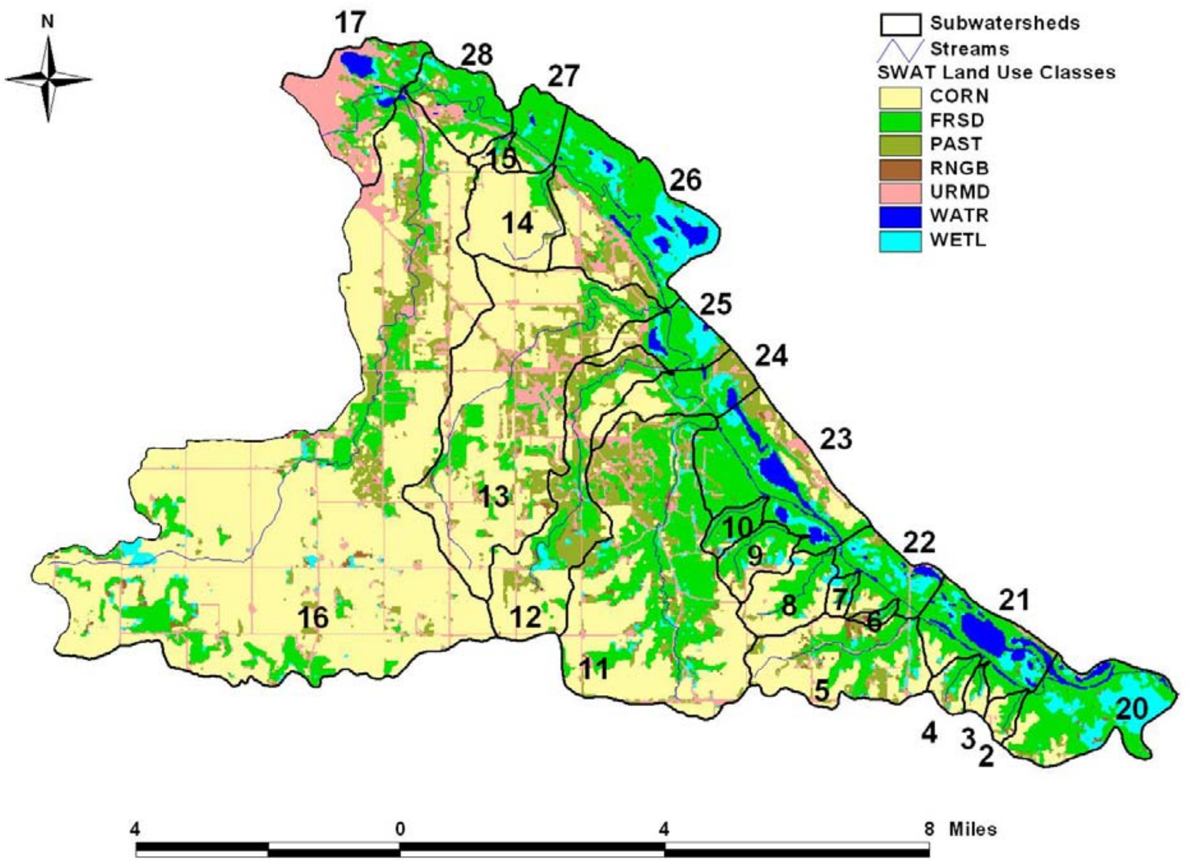


Figure B-2. SWAT Land Use Classification for the Lower Vermillion Watershed. Note that the mapped CORN class includes the interpreted CORN and MULCH land uses.

Table B-3. Definition of SWAT Land Use Classes for Lower Vermillion Model

SWAT Class	Definition
CORN	Conventional Corn-Soy Rotation
MULCH	Corn-Soy Rotation with Mulch Tillage
FRSD	Deciduous Forest
PAST	Pasture and Hay
RNGB	Scrub/Shrub
URMD	Medium Density Urban Land
WATR	Water
WETL	Wetland

Table B-4. Land Use Distribution (acres) for Lower Vermillion Direct Drainage

Subbasin	URMD	CORN	MULCH	PAST	FRSD	WATR	WETL	RNGB	TOTAL
2	5.3	44.3	44.3	2.9	85.4	0.0	1.1	5.6	188.8
3	1.3	36.3	36.3	0.2	44.7	0.0	8.7	1.1	128.5
4	5.6	48.0	48.0	26.5	100.5	0.0	18.7	0.7	248.0
5	122.8	454.5	454.5	180.8	516.6	0.0	60.7	50.7	1840.5
6	4.0	8.2	8.2	8.5	40.0	0.0	4.9	8.2	82.1
7	0.0	33.0	33.0	8.2	46.9	0.0	25.4	0.7	147.2
8	19.1	229.5	229.5	18.5	271.3	0.0	38.7	4.7	811.3
9	22.7	72.9	72.9	26.7	278.9	0.0	44.9	12.2	531.3
10	7.3	6.8	6.8	8.9	240.6	0.0	12.5	8.9	291.8
11	540.9	1125.7	1125.7	743.0	2050.5	0.4	155.5	86.1	5827.6
12	165.9	541.6	541.6	629.8	478.8	0.0	71.2	39.4	2468.4
13	687.0	1688.1	1688.1	877.8	651.6	0.0	9.8	29.6	5631.9
14	43.8	500.3	500.3	51.8	95.9	0.0	2.2	0.2	1194.5
15	6.9	55.8	55.8	11.1	34.2	0.0	3.3	0.4	167.7
16	1251.9	6012.3	6012.3	1272.1	1849.2	6.2	248.0	150.1	16802.2
17	756.6	34.8	34.8	73.6	402.1	106.1	67.8	29.6	1505.4
18	9694.0	13749.2	13749.2	4549.5	5627.3	343.6	1882.6	751.9	50347.3
19	1021.7	6272.9	6272.9	800.6	578.0	1.3	166.1	88.1	15201.6
20	13.3	71.9	71.9	28.7	897.6	85.4	483.5	27.6	1680.0
21	10.7	65.8	65.8	18.9	616.7	318.9	143.4	8.5	1248.7
22	24.9	32.9	32.9	42.9	493.5	50.3	170.8	9.1	857.3
23	128.5	125.5	125.5	209.3	1116.6	266.7	154.8	14.5	2141.4
24	61.2	114.5	114.5	139.0	337.8	33.4	81.8	3.1	885.4
25	27.6	40.6	40.6	77.4	334.9	47.8	143.4	6.4	718.8
26	219.1	213.2	213.2	212.8	1141.3	164.6	518.2	44.5	2726.8
27	14.2	12.2	12.2	5.6	426.3	5.8	29.6	5.8	511.7
28	103.9	64.2	64.2	70.9	540.9	6.0	48.0	13.1	911.2

B.4 Soils Data

STATSGO state soils data were obtained from the NRCS for Dakota and Goodhue Counties. The database includes information on soil composition, texture, erodibility, slope, etc. The SWAT model draws information from the STATSGO database to extract modeling parameters for each soil class. Figure B-3 shows the distribution of STATSGO soil classes in the watershed.

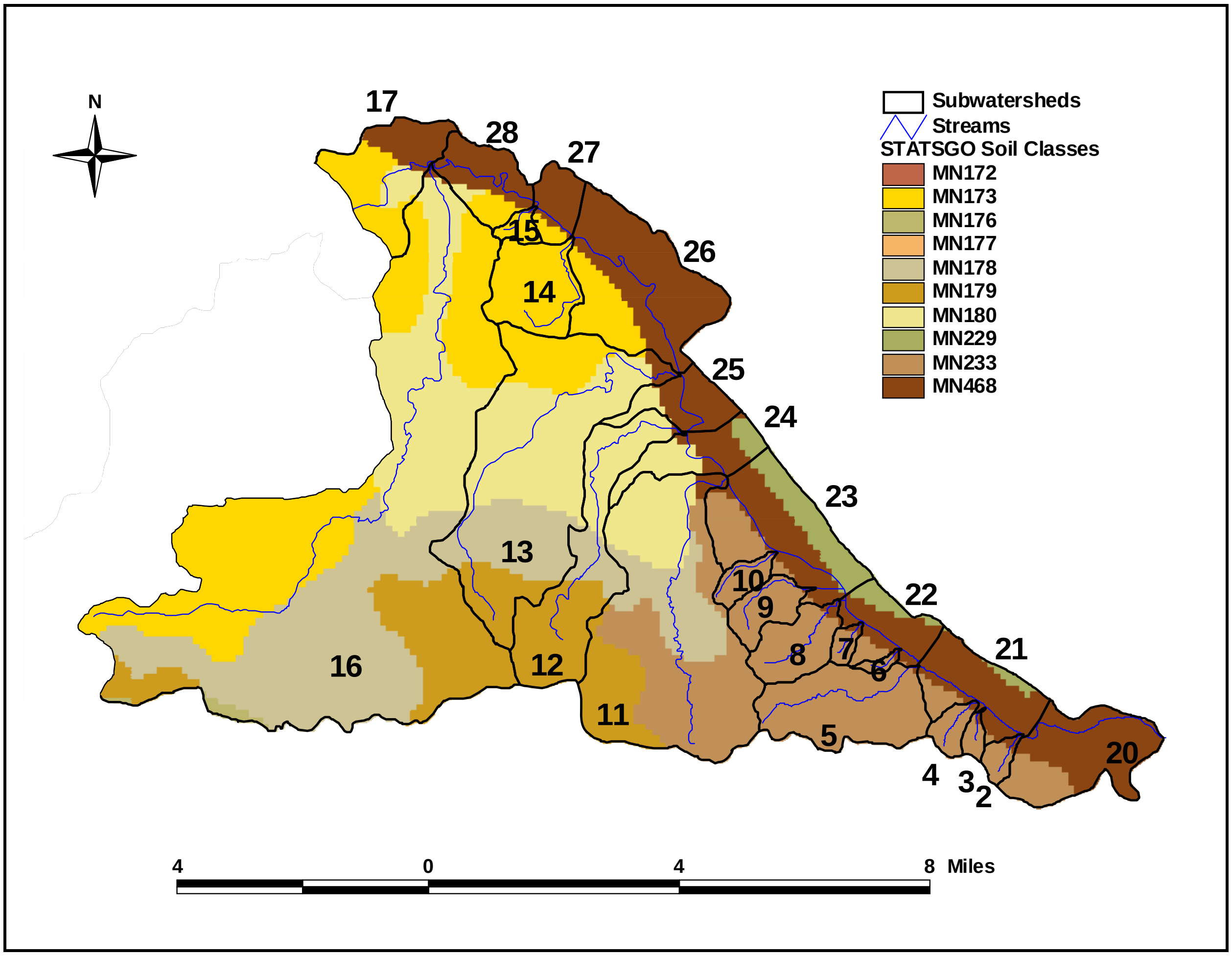


Figure B-3. STATSGO Soil Classification for the Lower Vermillion Watershed

B.5 Development of Hydrologic Response Units

BASINS 3.1 overlays land use and soils data to define hydrologic response units (HRUs) for use in either a SWAT or HSPF application. Due to variations in land use and soil modeling parameters, each HRU responds uniquely to weather events. For this application, the percent area thresholds were set to 5 percent for both the soil and land use coverages. Each modeling subwatershed in the Lower Vermillion River has between one and 15 HRUs.

SWAT describes operations on agricultural land through management (.mgt) files. Basic parameters for the simulation are described in Table B-5. Management also affects surface runoff. This is expressed in the model through assignment of the Curve Number for antecedent soil moisture condition II (average conditions), as summarized in Table B-6.

For row crop lands, a 2-year corn-soy rotation is assumed. To avoid biases in the model that would occur if all cropland was assumed to be simultaneously in one crop, the first-year crop was alternated between corn and soybeans. In addition, the plowing-replanting year for alfalfa hay was varied between subbasins.

Table B-5. Agricultural Management for SWAT Model

Cover	Tillage	Plant	Harvest	Fertilization
Corn (conventional)	Disk (Apr. 28), Chisel plow (Oct. 25)	May 1	Oct. 15	100 Lb/ac N
Corn (mulch tillage)	Mulch tiller (Apr. 28) Chisel plow (Oct. 25)	May 1	Oct. 15	100 Lb/ac N as anhydrous ammonia
Soybeans (conventional)	Disk (May 13) Chisel Plow (Oct. 25)	May 15	Oct. 1	None
Soybeans (conservation tillage)	Chisel Plow (Oct. 25)	May 15	Oct. 1	None
Alfalfa	Field Cultivator (1st yr, Apr. 13), chisel plow (3rd yr, Sep. 8)	Every 3 years (Apr. 15)	5/31, 7/15, 9/1	None

Table B-6. Curve Numbers (Antecedent Moisture Condition II) for Agricultural Lands

Cover	Hydrologic Soil Group B	Hydrologic Soil Group C	Hydrologic Soil Group D
Alfalfa Hay	72	81	85
Conventional Corn	78	85	89
Mulch Tillage Corn	75	82	85
Soybean	72	81	85
Bare Soil	86	91	94

B.6 Meteorology

SWAT requires specification of meteorological forcings, including precipitation, temperature, potential evapotranspiration (PET), and other variables. For precipitation and temperature, the nearest Summary of the Day stations were used, with subbasins 1 to 11 and 20 to 23 assigned to the station at Red Wing Dam 3 (Coop station 216822; Lat: 44.62443 Lon: 92.6230), and subbasins 12 to 17 and 24 to 28 assigned to the station at Hastings Dam 2 (Coop station 2132567; Lat: 44.76541 Lon: 92.86226). Missing values at these stations were patched by reference to the records at the St. Paul Municipal Airport (WBAN 14922).

Daily solar radiation and pan evaporation data for the growing season were provided by the Climatological Observatory, Department of Soil, Water, and Climate, College of Food, Agricultural and Natural Resource Sciences, University of Minnesota (personal communication from David L. Ruschy, University of Minnesota to Justin Watkins, MPCA, Oct. 4, 2006) under the stipulation that the data were to be used solely for the purposes of this project and not published or distributed in any manner. The PET series for the non-growing season was calculated using the Penman method. Records from the St. Paul Municipal Airport (WBAN 14922) were used for humidity and wind. Although MCES operated a meteorological station at Lake City from 2000 to 2006, the data from the University of Minnesota were used because they included the entire simulation period.

B.7 Sediment Simulation

SWAT uses the Modified Universal Soil Loss Equation (MUSLE) to simulate upland erosion. The MUSLE (Williams, 1975, 1995) uses the familiar Universal Soil Loss Equation (USLE) factors for soil erodibility (K), length and slope (LS), cover (C), and management practices (P), but omits the rainfall erosivity factor. USLE provides field-scale estimates of soil loss, while sediment yield at the watershed scale requires application of an empirical sediment delivery ratio. In contrast, MUSLE estimates sediment yield at the subwatershed scale, based on runoff volume, peak runoff rate, USLE factors (derived from the soils coverage in the project GIS), and drainage area. This avoids the need for explicit estimation of a delivery ratio or an erosivity factor.

There is a theoretical problem with the SWAT implementation of MUSLE. Specifically, the calculation is made at the land use/soil overlay fragment (HRU) scale, rather than the subwatershed scale. Channel length, which affects time of concentration and in turn peak runoff rate, is apportioned by SWAT to the individual HRUs on an area-weighted basis. In fact, it is the subwatershed time of concentration and peak flow rate that affect sediment retention, and calculation with an artificially shortened channel length tends to lead to an underestimation of time of concentration, an overestimation of peak runoff relative to runoff volume, and a corresponding overestimation of sediment delivery. The error increases as the number of HRUs in a subwatershed increases – causing a noticeable effect of number of HRUs on sediment prediction, as noted in Jha et al. (2004). In addition, the coefficient in the original MUSLE equation was developed on a relatively small number of sites and may well vary (SWAT uses the coefficient originally proposed by Williams in 1975, but a later (Williams, 1995) version uses a lower coefficient). Finally, the approach ignores deposition in smaller channels that are not included in the reach network.

We addressed these problems by modifying the code to include options to adjust the MUSLE. Unfortunately, there are no data sets for calibration of the SWAT model predictions in the minor tributaries draining directly to the Lower Vermillion River. The model does, however, need to produce predictions that are consistent with observed water quality in the Lower Vermillion River itself. Based on calibration of the W2 model and experience with similar watersheds in the Midwest, the MUSLE coefficient was reduced to 25 percent of the default value for the Vermillion River application.

Additional modifications to the model code were needed to simulate channel degradation in first-order streams (SWAT addresses channel degradation, but turns off the calculation for first-order streams by default). Channel degradation is known to be an important source of sediment in the system, particularly as upland streams descend the scarp to the Mississippi valley. Bank failure in Etter Creek has been a specific concern. In 2002, the Dakota County Soil and Water Conservation District (SWCD) began a watershed assessment of Etter Creek with the intention of developing a streambank restoration plan for one of the severely eroded banks. The Dakota County SWCD teamed with the National Parks Service (NPS) and the Association of Metropolitan Soil and Water Conservation Districts (MASWCD) to identify the major sources of sediment and the areas of highest erosion and to assess overall channel morphology (Dakota County SWCD, 2002). During this assessment, the team identified the section of Etter Creek just downstream of three large culverts under Red Wing Boulevard as the most severely eroded segment of the Creek. Bank height along this segment was 50 feet, and plans for restoration were outlined in the report. The final project report (Dakota County SWCD, 2003) stated that restoration of the streambank below Red Wing Boulevard was completed in the fall of 2003 by realigning and lengthening the channel. The new channel was positioned 50 feet from the original streambank. In October 2006, Dakota County SWCD stated that only qualitative visual reconnaissance had been conducted on this project, and no attempts had been made to estimate sediment loading resulting from bank erosion either before or after the project (personal communication from Brian Watson, Dakota Co. SWCD to Kevin Kratt, Tetra Tech, Oct. 3, 2006).

The channel sediment routing component of SWAT was implemented as recommended in the SWAT manual, with most parameters set to defaults. Channel erodibility was set to 1/10 of the surrounding soil erodibility, as recommended, and 20 percent of the channel was assumed to be without any vegetative cover or armoring protection from scour. Riparian buffers were assumed to be small in the upland areas (average of 1 m); however, in the lowland floodplain areas much larger buffers were assigned (10 m) to reflect the fact that there are typically wetlands, assumed to have significant trapping capability, between managed land and the Vermillion main channel.

B.8 SWAT Model Results

As noted above, no calibration data are available for the local tributaries. Therefore, the model was run with default parameters, except as noted above. Resulting predicted loads are summarized by model subbasin in Table B-7.

Table B-7. Summary of Predicted Average Annual Loading Rates from Local Tributaries to the Vermillion River (Jan. 1995 – Aug. 2004)

Model Subbasin	Area (km^2)	Flow (1000 m^3/yr)	Sediment (1000 kg/yr)	Inorganic N (kg/yr)	Organic N (kg/yr)	Inorganic P (kg/yr)	Organic P (kg/yr)
2	0.778	114	63	67	107	10	18
3	0.542	94	41	47	65	6	11
4	1.03	152	48	78	79	8	14
5	7.59	1222	541	1498	1004	109	170
6	0.332	40	7	11	9	1	2
7	0.589	103	28	44	45	5	9
8	3.29	554	267	575	480	48	82
9	2.15	258	92	228	173	18	29
10	1.18	85	2	114	1	2	0
11	23.8	4420	1007	7368	2446	319	375
12	10.0	1841	182	3283	615	96	85
13	22.6	5205	344	9231	853	225	125
14	4.83	951	71	734	215	22	28
15	0.628	114	32	73	113	8	15
16	68.3	14908	1890	21585	5839	739	824
17	6.23	945	23	755	154	101	22
20	7.08	590	13	1251	33	18	5
21	5.13	290	12	479	29	7	4
22	3.51	279	7	524	17	8	7
23	8.79	819	17	1071	74	20	10
24	3.63	685	19	1146	51	18	8
25	2.95	358	6	778	16	10	3
26	11.2	1375	60	1798	291	37	41
27	2.11	103	0	186	0	3	0
28	3.75	421	19	481	82	12	12
Total	202	35926	4791	53405	12791	1850	1899

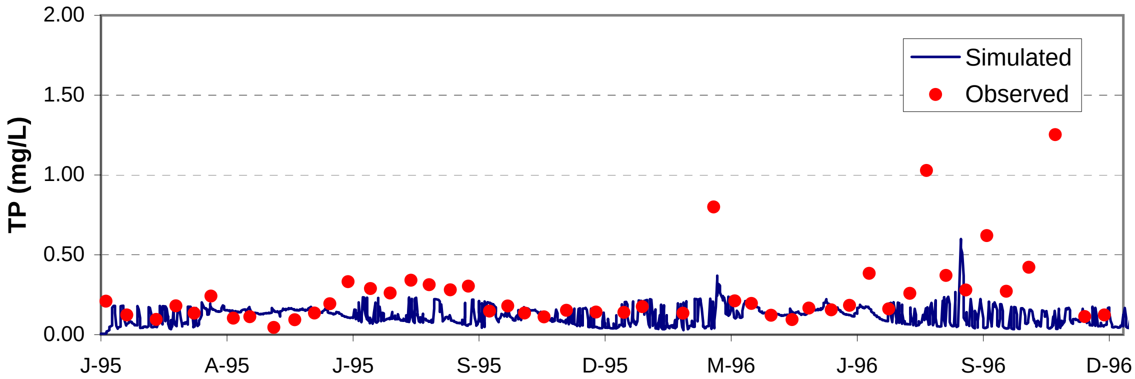
B.9 References

Dakota County SWCD. 2002. Etter Creek Watershed Assessment and Bank Restoration Project, Interim Report. Dakota County Soil and Water Conservation District.

Dakota County SWCD. 2003. Etter Creek Watershed Assessment and Bank Restoration Project, Final Report. Dakota County Soil and Water Conservation District in cooperation with Ravenna Township.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams, and K.W. King. 2002. Soil and Water Assessment Tool, Theoretical Documentation, Version 2000. Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Temple, Texas.

APPENDIX C. MODEL CALIBRATION RESULTS FOR TWO YEAR PERIODS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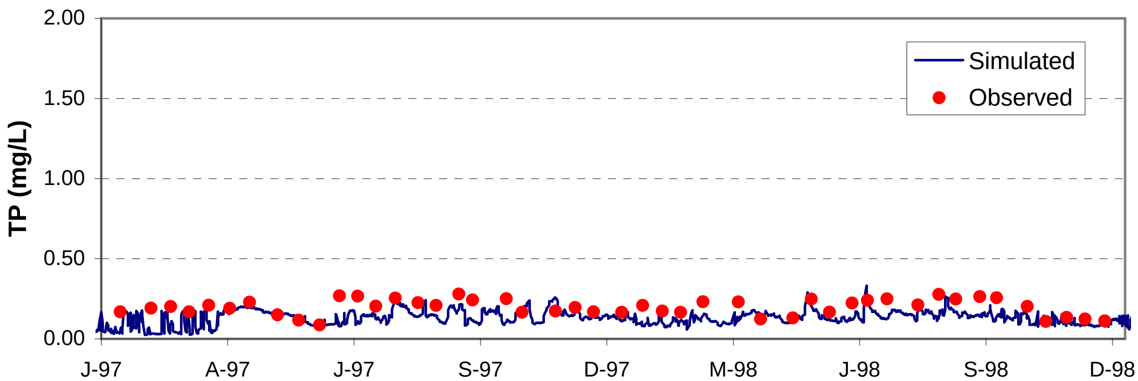
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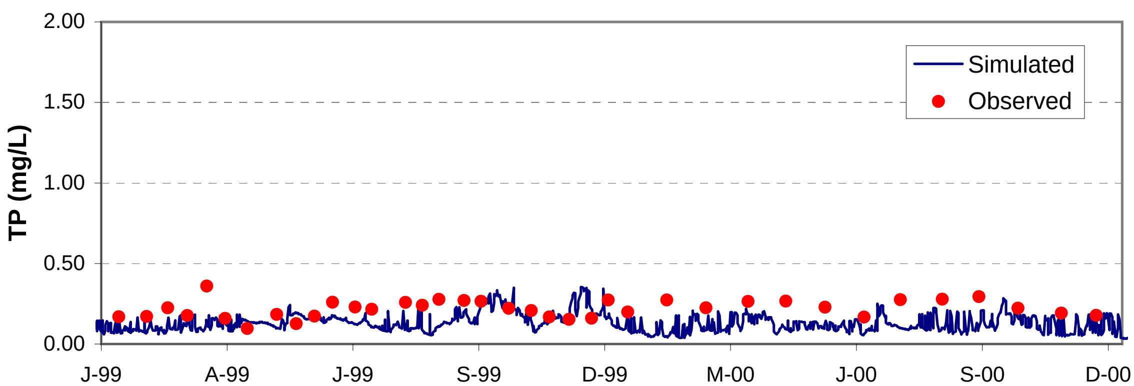
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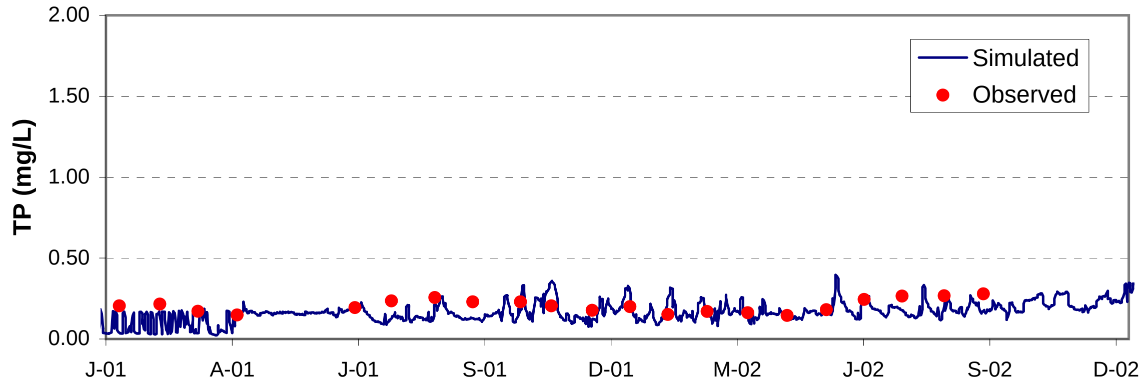

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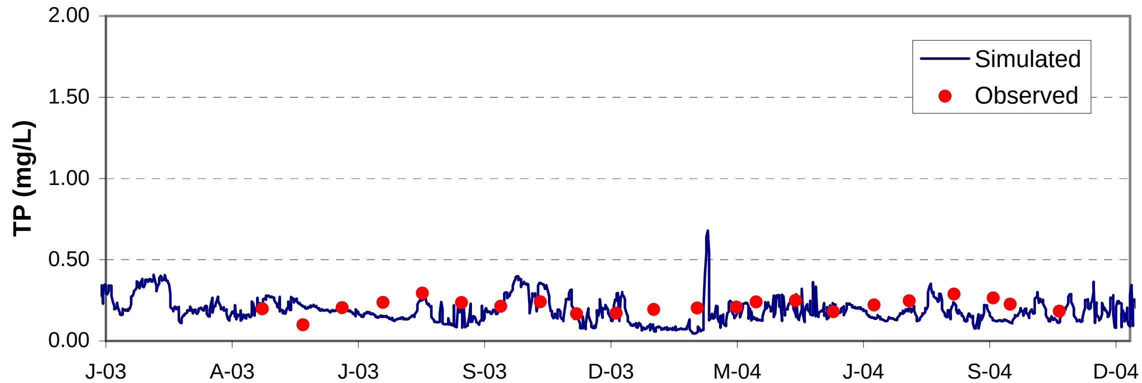

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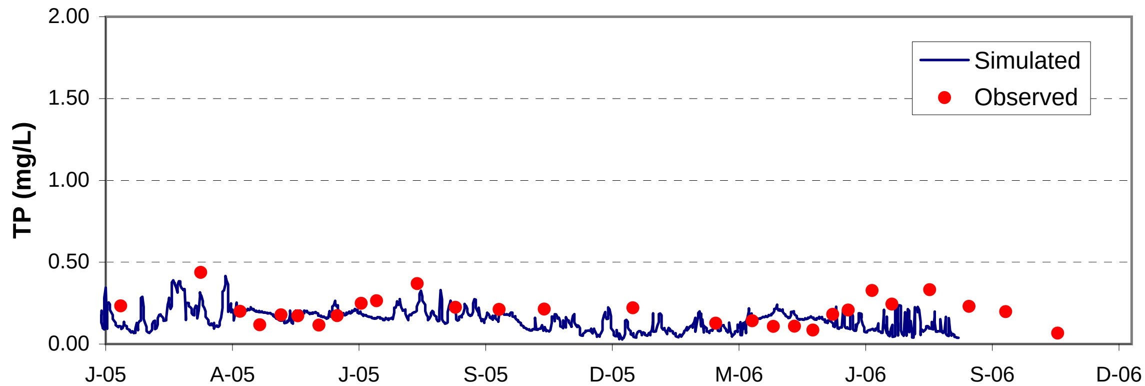

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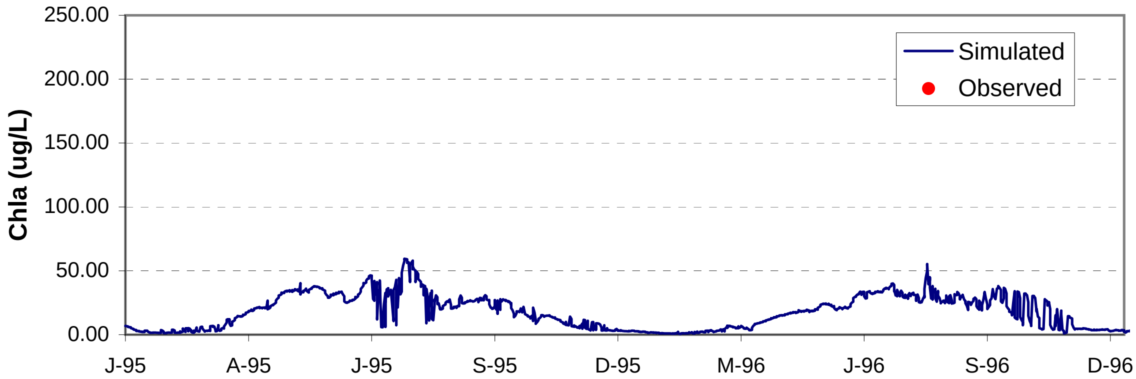
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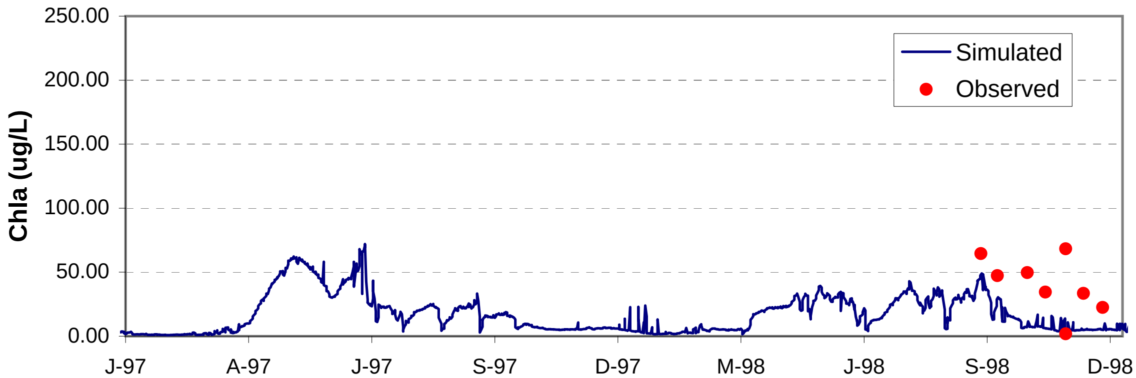
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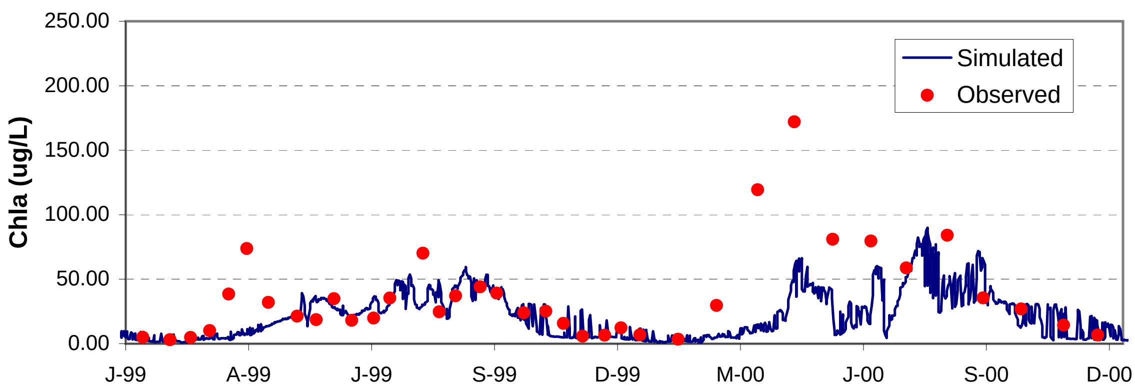
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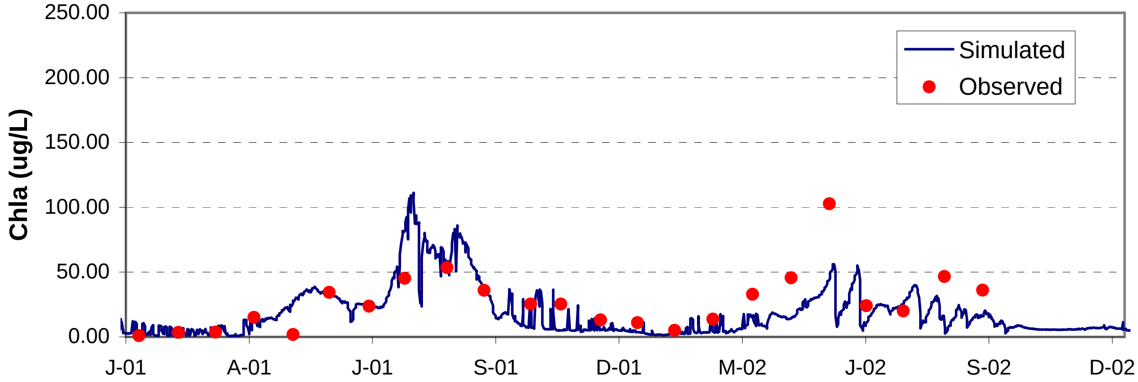
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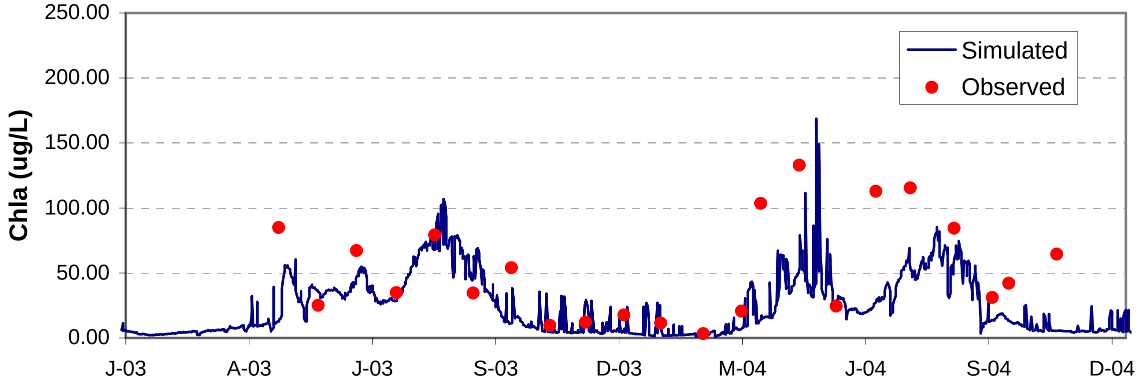
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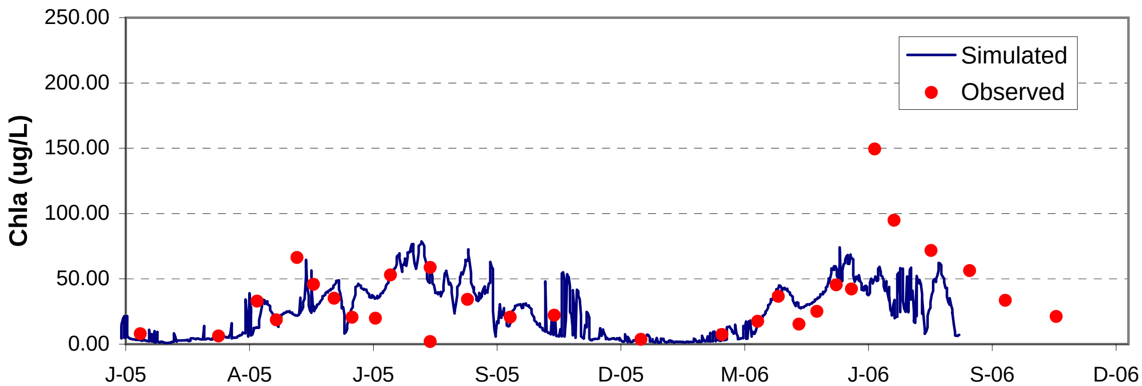
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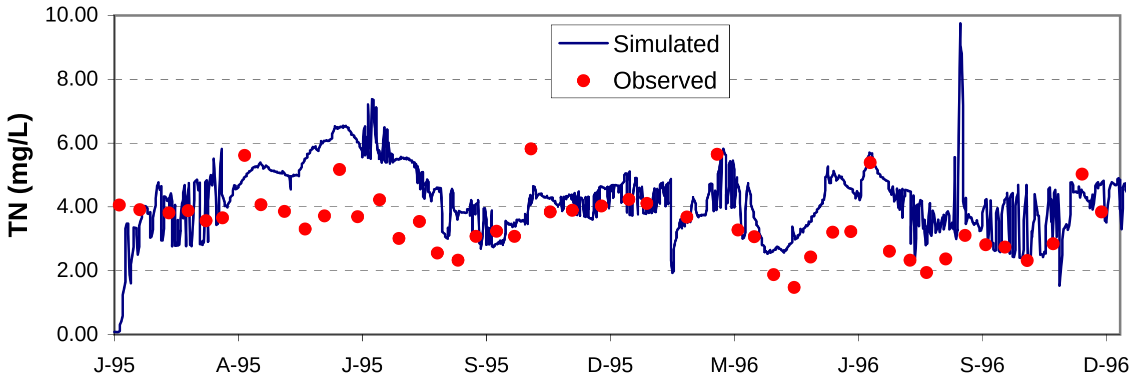
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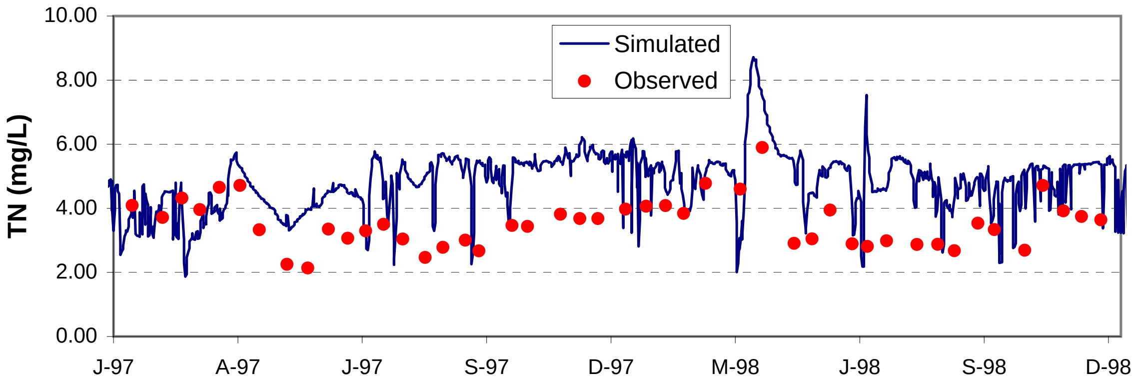
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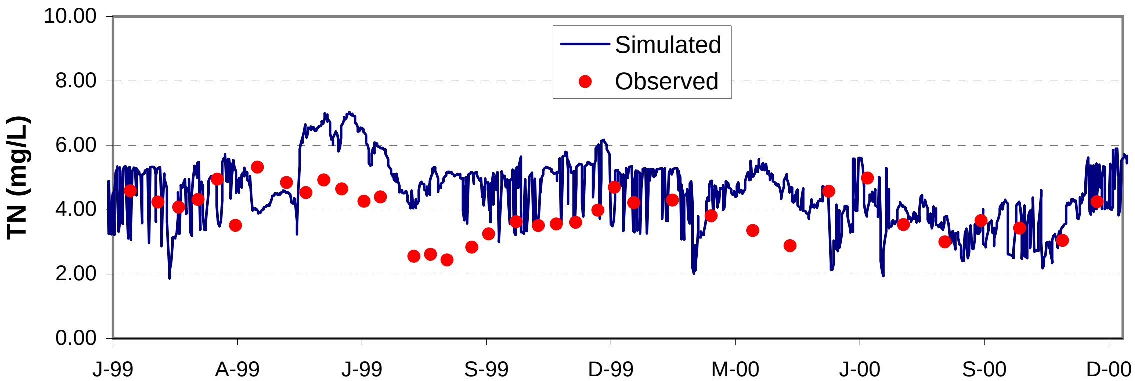
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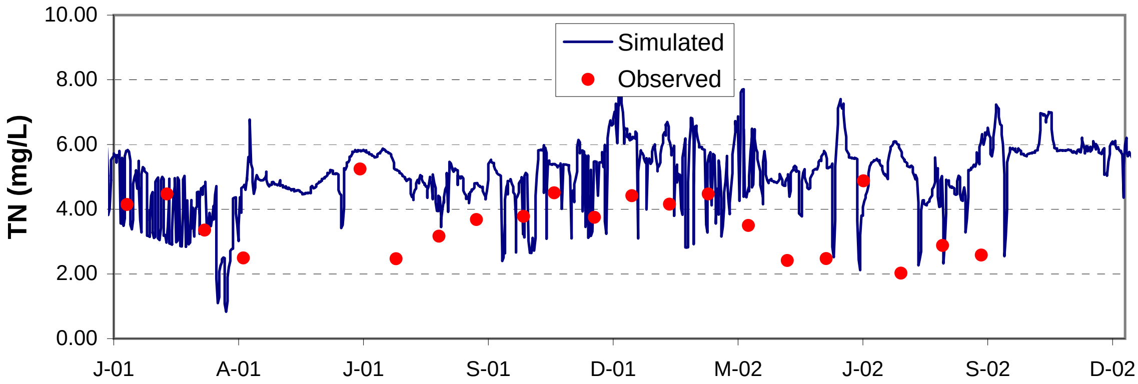
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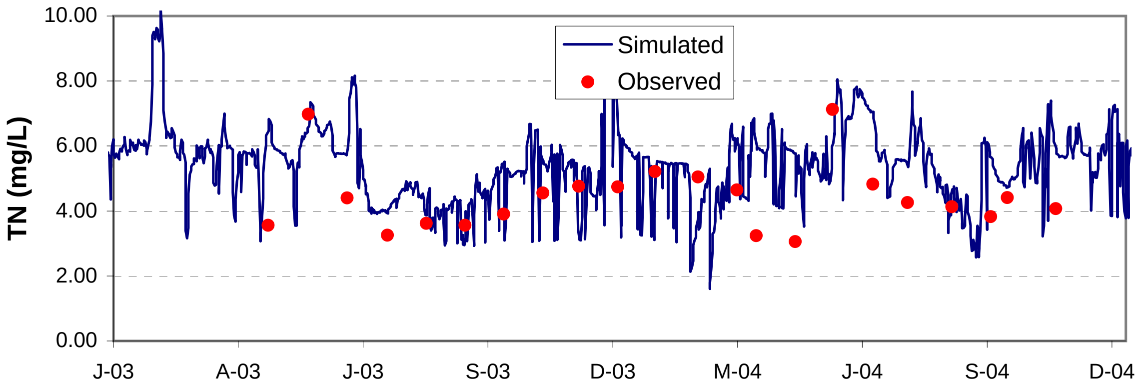
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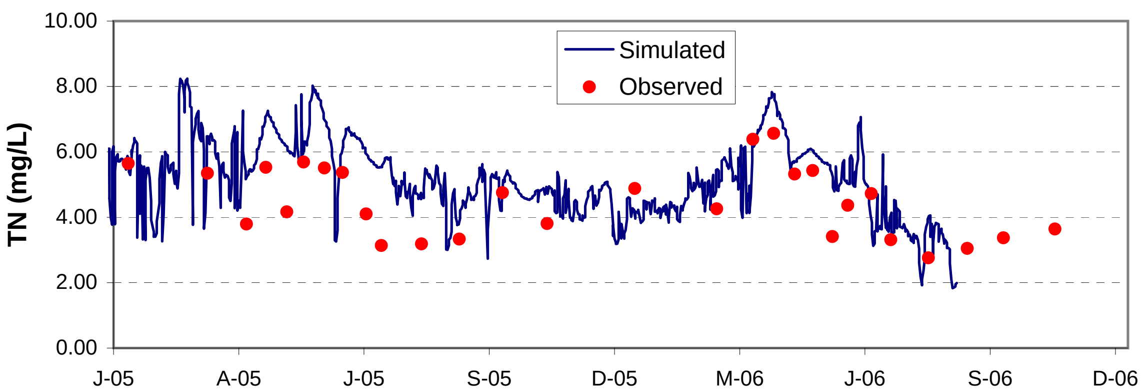
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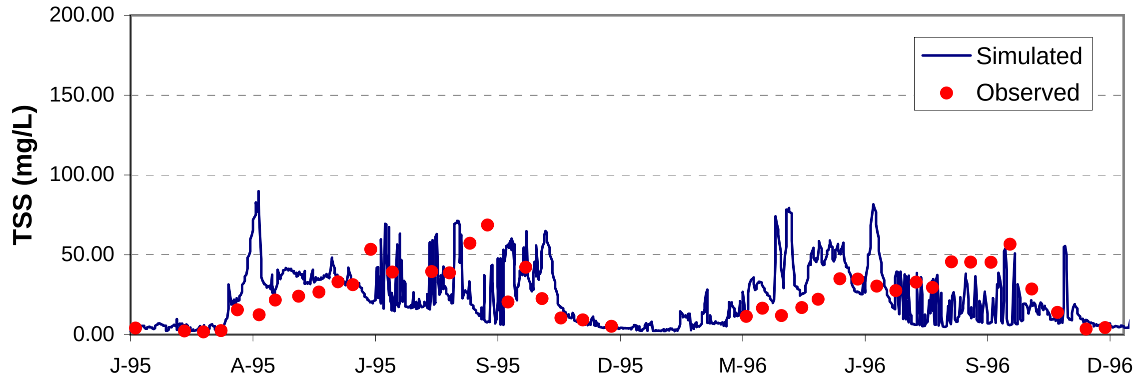
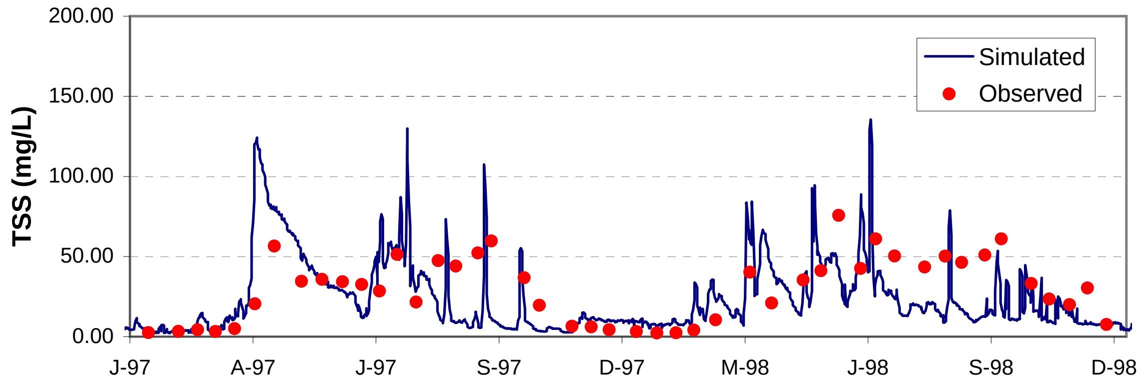
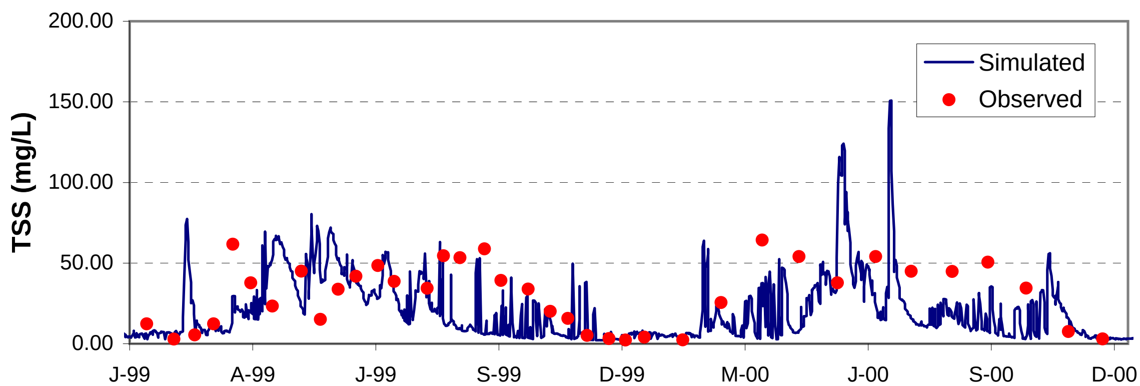
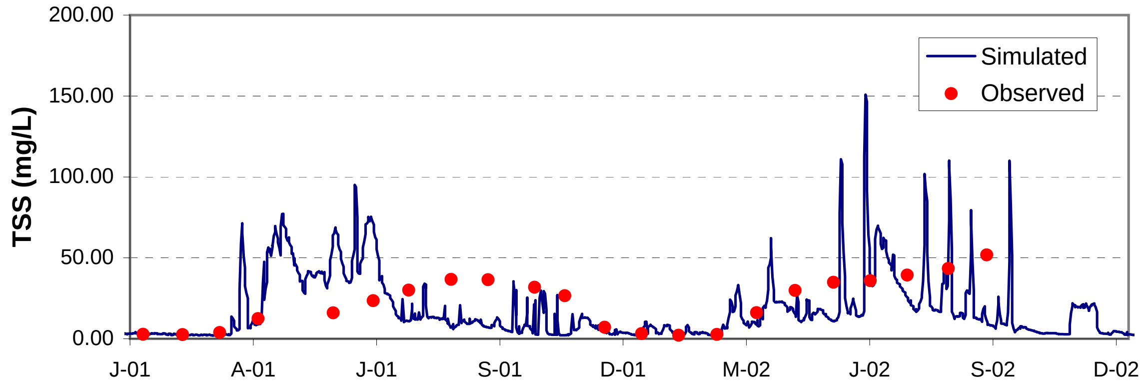
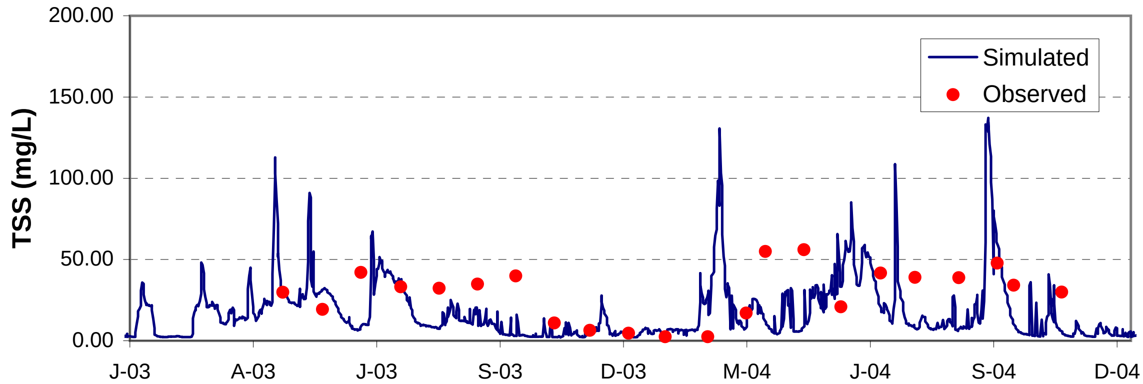
0.00
TN (mg/L)
Simulated
Observed
J-05
A-05
J-05
S-05
D-05
M-06
J-06
S-06
D-06

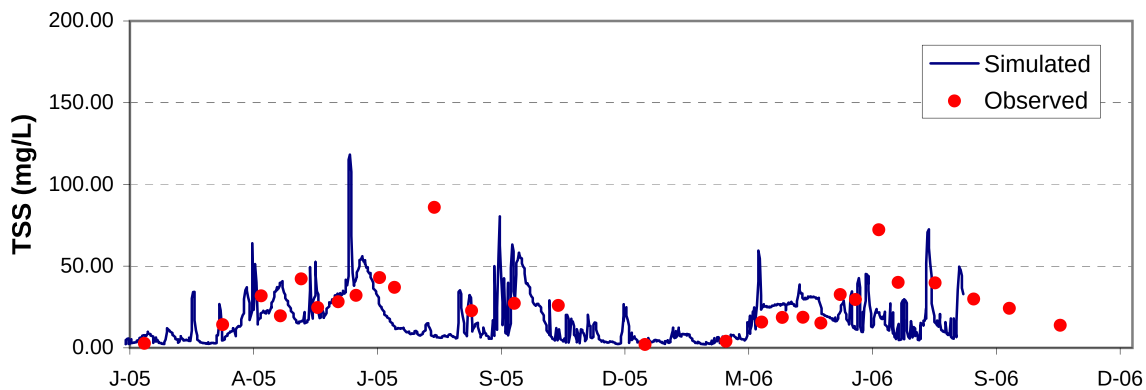

TSS (mg/L)
200.00
150.00
100.00
50.00
0.00
Simulated
Observed
J-95
A-95
J-95
S-95
D-95
M-96
J-96
S-96
D-96

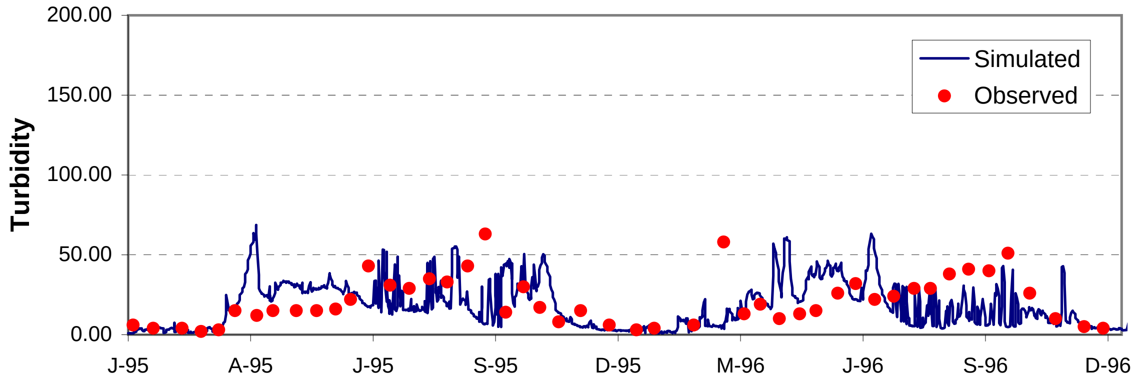

TSS (mg/L)
200.00
150.00
100.00
50.00
0.00
Simulated
Observed
J-97
A-97
J-97
S-97
D-97
M-98
J-98
S-98
D-98

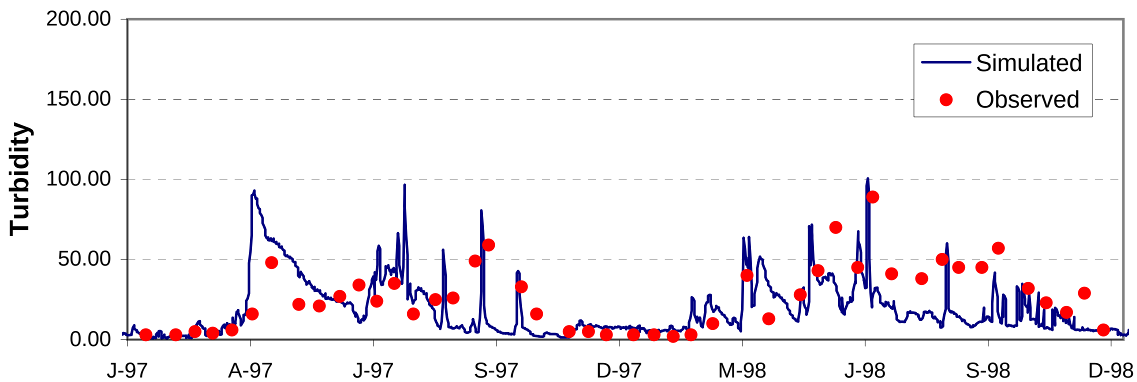

TSS (mg/L)
200.00
150.00
100.00
50.00
0.00
Simulated
Observed
J-99
A-99
J-99
S-99
D-99
M-00
J-00
S-00
D-00

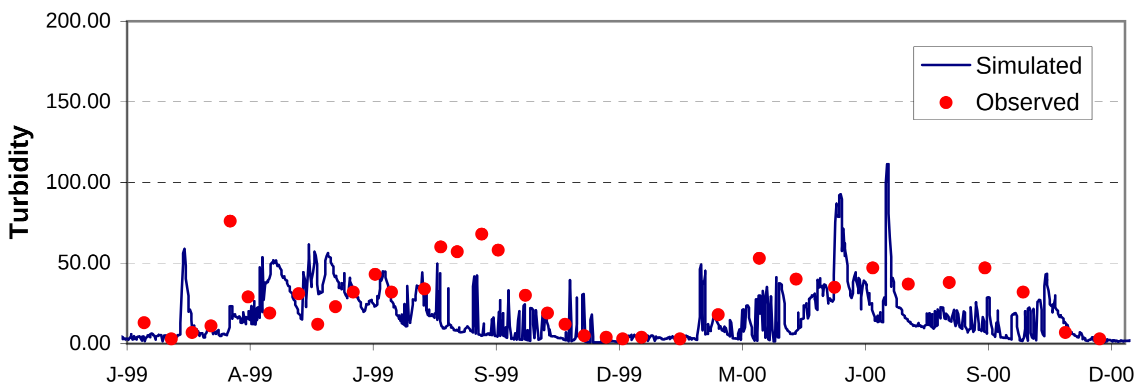

TSS (mg/L)
200.00
150.00
100.00
50.00
0.00
J-01
A-01
J-01
S-01
D-01
M-02
J-02
S-02
D-02
Simulated
Observed

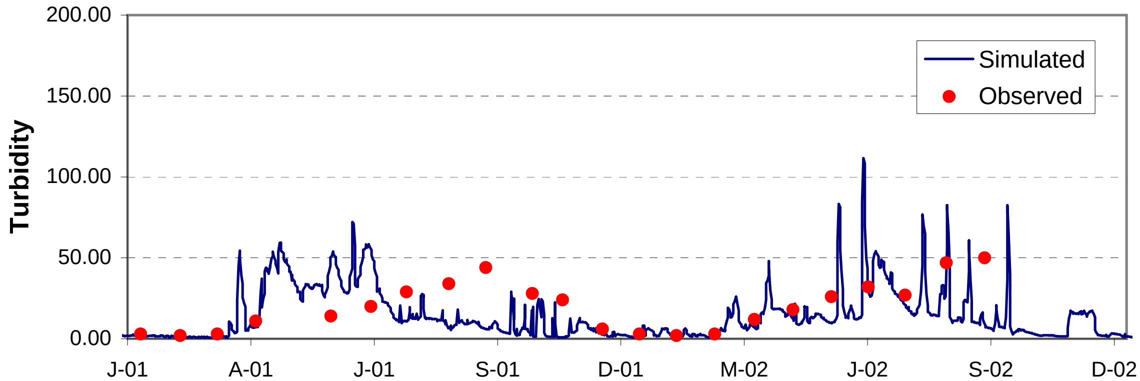

TSS (mg/L)
200.00
150.00
100.00
50.00
0.00
J-03
A-03
J-03
S-03
D-03
M-04
J-04
S-04
D-04
Simulated
Observed


TSS (mg/L)
200.00
150.00
100.00
50.00
0.00
J-05
A-05
J-05
S-05
D-05
M-06
J-06
S-06
D-06
Simulated
Observed

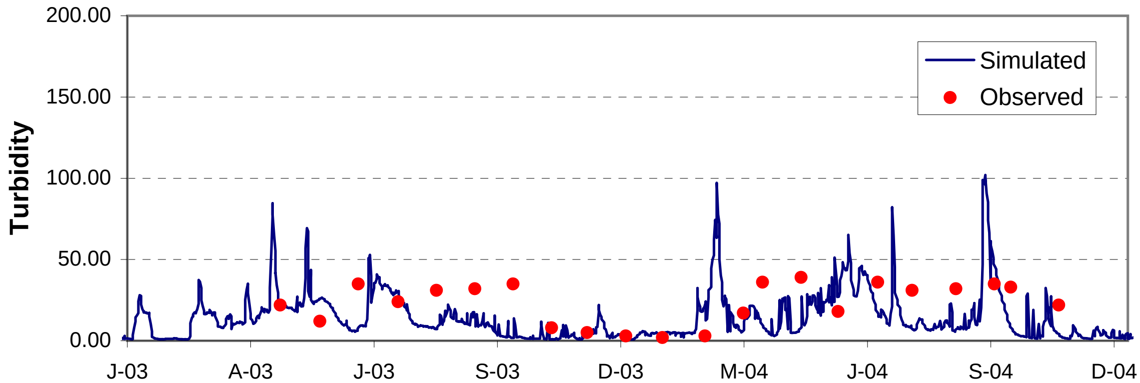

Turbidity
200.00
150.00
100.00
50.00
0.00
Simulated
Observed
J-95
A-95
J-95
S-95
D-95
M-96
J-96
S-96
D-96


Turbidity
200.00
150.00
100.00
50.00
0.00
Simulated
Observed
J-97
A-97
J-97
S-97
D-97
M-98
J-98
S-98
D-98

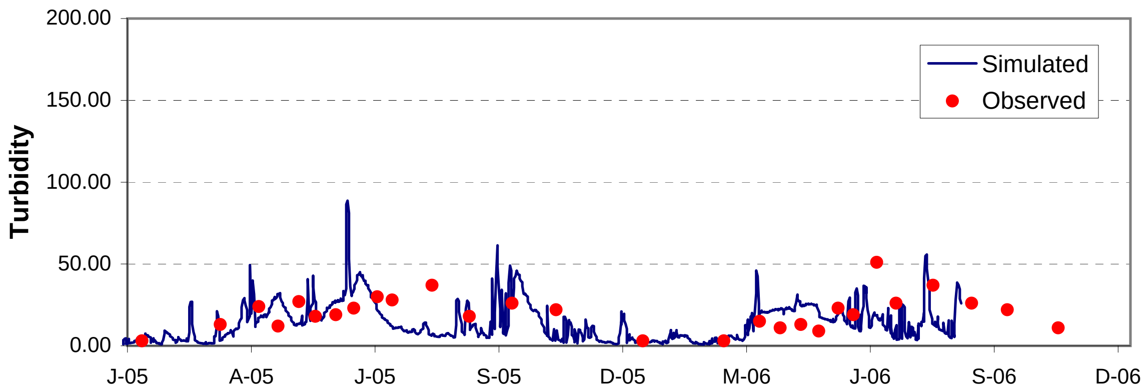

Turbidity
200.00
150.00
100.00
50.00
0.00
Simulated
Observed
J-99
A-99
J-99
S-99
D-99
M-00
J-00
S-00
D-00



Turbidity
200.00
150.00
100.00
50.00
0.00
J-01
A-01
J-01
S-01
D-01
M-02
J-02
S-02
D-02
Simulated
Observed



Turbidity
200.00
150.00
100.00
50.00
0.00
J-03
A-03
J-03
S-03
D-03
M-04
J-04
S-04
D-04
Simulated
Observed



Turbidity
200.00
150.00
100.00
50.00
0.00
J-05
A-05
J-05
S-05
D-05
M-06
J-06
S-06
D-06
Simulated
Observed

Appendix C

Lower Vermillion River Watershed Turbidity TMDL:

Upper Vermillion River Time Series

Prepared for
Minnesota Pollution Control Agency

Prepared by:
Tetra Tech, Inc.

The Empire WWTP discharges to the Vermillion River at RM 15.6. It is the only major discharge to the Vermillion, and has an average effluent flow of about 8.5 MGD, which can constitute a significant fraction of the total flow in the Upper Vermillion under low flow conditions. Because of its potential impact on the Vermillion and planned increases in permit capacity, the effluent from this plant will in future be piped to the Mississippi River.

Removal of the Empire discharge will result in a significant reduction in the nutrient loads at the boundary of the Lower Vermillion model. A revised set of boundary time series at Hastings has been constructed to represent this scenario.

The new time series are approximate, because a water quality has not been constructed for the 12.9 miles between Empire and Hastings. Simply subtracting the existing Empire loads from the existing time series is not appropriate – and would often result in negative loads – as it is necessary to account for losses and dispersion occurring between Empire and Hastings.

Cathy Larson at MCES provided spreadsheets containing daily flows and approximately biweekly estimates of nutrient loads in the Empire discharge. These loads were first processed to estimate the delivered loads at Hastings. The RF1 files estimate that stream velocity in the Upper Vermillion is approximately 0.51 fps at 7Q10 flow and 0.91 fps at mean flow, translating to a travel time of 0.87 to 1.5 days. Approximate nutrient loss rates were calculated using the USGS SPARROW approach (Smith et al., 1997), using the national parametric instream decay coefficients for streams with flow less than 28.3 m^3/s (0.2584 and 0.3758 day^{-1} for TP and TN, respectively). The medians of the estimated 7Q10 and mean flow transmission fractions (73.9 % for TP and 64.5% for TN) were used to estimate the fraction of the wasteload that is delivered to Hastings.

These loads are assumed to be delayed by approximately 1 day between Empire and Hastings, based on the reported velocities. The estimated delivered load is occasionally greater than the estimated FLUX load with the Empire discharge present. This occurs primarily during low flow and may reflect temporary retention within the system. To account for this phenomenon, the delivered loads from the WWTP were first smoothed using a seven-day rolling average. When the resulting estimate of delivered load from Empire exceeded the FLUX load for a given day, the excess was accumulated and assigned to the next following day(s) in which an excess FLUX load as present. In addition, it was assumed that there was an irreducible minimum concentration always remaining in the stream (0.05 mg/L for TP, 1.0 mg/L for TN, and 0.5 mg/L for BOD5). Loads were not reduced below this concentration level, but conservation of mass is achieved by accumulating the excess to subsequent days.

The resulting output spreadsheet is formatted in the same way as the previous FLUX output. The following additional assumptions were made regarding individual parameters for the scenario with Empire WWTP removed:

Flow: Scenario flow is assumed to be directly equal to the monitored flow at Hastings minus the discharge from Empire on the previous day.

Total Phosphorus: Calculated as described above, with one additional refinement. The Empire plant went through a significant upgrade in September 2006, which significantly reduced phosphorus loads (by almost 90 percent). The existing FLUX output is fit to observed data that does not account for this upgrade – therefore, subtracting the reported Empire load from the FLUX estimate will leave an estimated residual load that is higher than it should be. This situation was addressed by first multiplying the existing FLUX estimate times (1 – E/H) x (1 + P/H), where E is the median of the pre-improvement Empire load estimated as delivered at Hastings, H is the median FLUX load at Hastings, and P is the median post-upgrade delivered load from Empire.

NO_2+NO_3: The load estimates from Empire are for total nitrogen. The fraction that is nitrate plus nitrite is likely to vary with ambient temperature. Further, significant uptake and transformations between nutrient species are likely to occur over the 12.9 miles between Empire and Hastings. I therefore calculated the average fraction of TN that is NO_2+NO_3 at Hastings on a monthly basis from the existing

FLUX model output. These monthly fractions were applied to the estimated TN delivered at Hastings with the Empire discharge eliminated.

TKN: TKN is assigned as the fraction of TN that is not NO_2+NO_3.

TSS: The contribution of the Empire discharge to inorganic solids is small, and the TSS concentrations observed at Hastings are strongly mediated by channel processes. Therefore, no changes in FLUX estimates of TSS were made for the scenario.

BOD5: MCES provided concentrations but did not provide estimates of BOD5 load from Empire, although it is clearly a significant contributor. BOD loads from the plant are fairly stable, but were affected by the plant upgrade. Therefore, effluent load was estimated based on effluent flow times average concentrations of 5.07 mg/L (prior to upgrade) or 2.20 mg/L (post upgrade). The delivered fraction at Hastings was estimated based on a typical decay rate of 0.22 day^{-1}.

TVS: Total volatile solids are not monitored at Empire, but can be significant in WWTP discharge. The existing FLUX output shows a reasonably stable relationship between TVS and TKN (average ratio of 10.7), with seasonal variation. Therefore, delivered TVS for the scenario was estimated by applying a monthly ratio to the predicted delivered TKN with Empire removed.