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For:
Mississippi Watershed Management Organization

MWMO Big River Study Report

June 2008

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A collaboration of professionals enhancing the value of our natural and cultural resources through science and design

Acknowledgements

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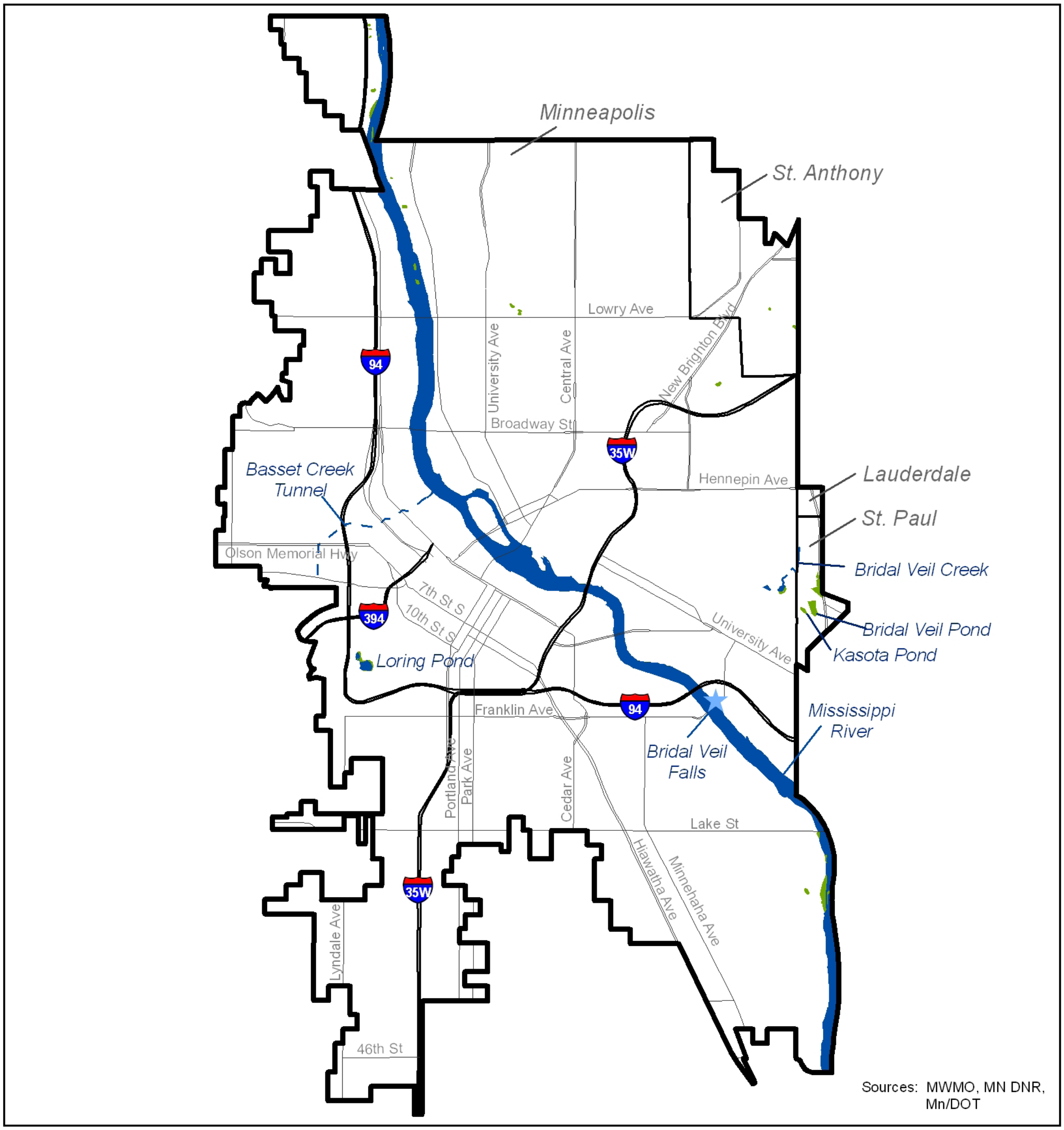

Surface Water Resources

Mississippi Watershed Management Organization
Watershed Management Plan

MWMO
Mississippi Watershed Management Organization

- MWMO Boundary
- Municipal Boundaries
- Bridal Veil Falls
- Streams
- Stormwater Tunnel
- Lakes & Rivers
- Wetlands

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Abbreviations

ADVM	Acoustic doppler velocity meter
CFS	cubic feet per second, volumetric flow rate
CWA	Clean Water Act (of 1977)
DO	Dissolved oxygen
EMAP	Environmental Monitoring and Assessment Program (of the USEPA)
FEMA	Federal Emergency Management Administration
HUC	Hydrologic Unit Code (of the USGS stream and river catalog)
L&D#1	Lock-and-Dam #1 at RM 848
LSAF	Lower St. Anthony Falls
LTRMP	Long-Term resource Monitoring Program (of the USGS)
MCES	Metropolitan Council Environmental Services
MDA	Minnesota Department of Agriculture
MDNR	Minnesota Department of Natural Resources
MPCA	Minnesota Pollution Control Agency
MSWM	Metropolitan Surface Water Management (Act of 1982)
MWMO	Mississippi Watershed Management Organization
NFM	National Field Manual (USGS TWRI Book 9, var. dated)
NPDES	National pollutant discharge elimination system
NPS	National Park Service
PCB	Polychlorinated biphenyls
RM	River mile (of the Mississippi River above its confluence with the Ohio River)
SAF	St. Anthony Falls
SC	Specific conductivity
SCWMC	Shingle Creek Watershed Management Commission
SDWA	Safe Drinking Water Act (of 1974)
T	Temperature
TWRI	Techniques in Water Resources Investigations (USGS book series)
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WWTP	Wastewater treatment plant

I. Background and Purpose of Study

The Mississippi Watershed Management Organization (MWMO) was established to conserve and preserve waters and natural resources, in compliance with the 1982 Metropolitan Surface Water Management (MSWM) Act as identified in Minnesota Statutes 103A through 103G in conformance with Minnesota Rules Chapters 8410 and 8420. The MWMO's Watershed Management Plan includes monitoring goals that are intended to meet or exceed the water resource protection requirements of the MSWM Act, including the protection of surface waters, groundwater, wetlands, and related natural resources (MWMO 2006). The goals of the MWMO that relate specifically to surface runoff and the Mississippi River are:

- Prevent flooding of streets and structures
- Mitigate the effects of drought
- Protect and enhance surface water quality
- Reduce nonpoint sources of pollution
- Improve surface water quality upstream of the MWMO area
- Control soil loss due to erosion
- Preserve, minimize impact to, and restore natural habitat, especially shorelines and habitat corridors

A. Purpose – Literature Review and Annotated Bibliography

In 2006, the MWMO developed plans to better achieve its responsibility for monitoring water quality in the Mississippi River. The MWMO is implementing a Monitoring Program that includes the mainstem of the Mississippi River as well as stormwater outfalls. The goal of the program is to establish baseline water quantity and quality data that can be used for the management of outfalls and receiving waters. For an accurate assessment of these systems, the MWMO will need to know where, how, and when to sample the Mississippi River, given the patterns of hydraulic mixing that occur in the river as it passes through the watershed.

The purpose of this report is to provide the MWMO with the information necessary to develop new monitoring protocols that will measure progress toward the above goals, given the findings (or gaps) in the hydraulic and pollutant mixing literature. The reporting process began with an extensive literature review on the topics of hydraulic mixing in large river systems and monitoring protocols appropriate for large river systems. This report includes an annotated bibliography summarizing the literature review, an assessment of mixing processes in big rivers and the big river characteristics that affect mixing, a delineation of the hydraulic mixing reaches of the Mississippi River within the MWMO area, and a description of the big river characteristics that influence mixing in each reach. In addition, this report discusses the components of a thorough monitoring protocol, summarizes the activities of other monitoring agencies within the MWMO area, and discusses various monitoring protocols that may achieve the monitoring goals of the MWMO. The Big River Study should support the MWMO in its plan to revamp its Water Management Plan.

B. Environmental Setting

Major Drainage Areas Contributing to the MWMO Area

The Mississippi River at the MWMO receives drainage from approximately 19,680 square miles (USACE 2004a). Much of this drainage area is rural woodland and agriculture with large urban communities of St. Cloud, Minneapolis, and surrounding communities. From upstream areas down to the MWMO border, the percentage of agricultural, forest, and wetlands decreases, while the percentage of residential, commercial, and turf lands increases (MDH 2001). The USGS website provides a good description of the watershed upstream of the MWMO:

The Headwaters' reach, located entirely within Minnesota (Fig. 2), has the steepest gradient, exiting Lake Itasca at 440 meters above mean sea level and dropping 204 meters along its 794-kilometer path to St. Anthony Falls, Minnesota (Fremling et al. 1989). This reach passes through spruce swamps, wildrice beds, natural lakes, beds of extinct glacial lakes, artificial impoundments, rapids, and dams (Waters 1977; MacGregor 1995). Beginning as a small, clear stream, the Headwaters gradually are stained a reddish-brown by natural organic acids leached from bog vegetation in the basin. The Mississippi River is a remote stream from Lake Itasca to Bemidji, meandering through corridors flanked by high, pine-topped sand banks, swampy lowlands, alder thickets, wildrice beds, and cattail marshes.

Approaching Bemidji, the wilderness character of the river is gradually lost because of human development. At Bemidji, the river flows through Lakes Irving and Bemidji and then through Stump, Big Wolf, Andrusia, Cass, Winnibigoshish, and Pokegama lakes (Fremling et al. 1989). The outlets of Lakes Winnibigoshish and Pokegama were dammed in 1891 and 1884 as part of a U.S. Army Corps of Engineers navigation and flood-control system that included four other dammed reservoir lakes on Mississippi River tributaries. The Headwaters' dams are now used mainly for flood control, recreation, conservation, and related uses. None of the 11 dams between Lake Itasca and St. Anthony Falls have navigation locks.

In Aitkin County, Minnesota, the river channel meanders for 200 kilometers over a straight-line distance of 64 kilometers. Many meander loops have been cut off, forming crescent-shaped oxbow lakes that are reconnected with the river during high water. Between the cities of Aitkin and Brainerd, the river passes through the Cayuna Iron Range, winding through hilly, heavily forested moraine systems, as well as glacial outwash plains, sand dunes, and swamps. Coniferous forests once covered most of the area, but logging, burning, and farming have produced a mixture of coniferous and hardwood forests. From Brainerd to St. Anthony Falls the landscape is dominated by an extensive system of glacial outwash and alluvial deposits that have been entrenched by the Mississippi River from St. Cloud to Minneapolis. The Headwaters' reach has been described in detail by Waters (1977), Fremling et al. (1989), and MacGregor (1995).

For more detail about the subwatersheds and major tributaries upstream of the MWMO, please refer to Payne (1995).

Climate and Surficial Geology

The MWMO area experiences a northern temperate climate; Minneapolis-St. Paul receives 28 inches mean annual rainfall, and mean daily temperatures range from 0º to 90ºF. The landscape of the region has been strongly influenced by a history of glaciation: the bedrock geology is overlain by glacial till deposits from two major Wisconsin ice lobes, and large volumes of meltwater from the receding glaciers carved impressive riverine gorges in the region. As these glacial rivers flowed through bedrock valleys, the exposed limestone formed waterfalls as the underlying erodible sandstone was continuously undercut, causing the waterfalls to retreat upstream. Waterfalls can still be found today in the Mississippi River gorge at St. Anthony Falls, and within tributaries to the Mississippi River, at Hidden Falls and Minnehaha Falls.

The waterfalls in the region were attractions for the first European settlers, as a natural source of power, and gradually municipalities grew around them. Steamboats arrived on the upper Mississippi in the 1820s, and the St. Paul District of the Army Corps of Engineers was established in 1866 to improve the river for navigation (Anfinson 2003). Present-day fluvial dynamics in the Upper Mississippi River basin are dominated by a series of 29 lock-and-dam structures designed to maintain a minimum 9-foot channel depth for barge navigation. The navigation control structures, between Minneapolis, Minnesota and St. Louis, Missouri, create a staircase of shallow lakes that inundate former floodplains in their lower reaches. The Mississippi River within the MWMO area represents the top two or three steps of this staircase: 1) the upper and lower St. Anthony Falls dams are located at the midpoint of the MWMO reach of the Mississippi, and 2) Lock-and-Dam #1 is located at the southern boundary of the MWMO area.

Dominant Land Uses

The municipality of Minneapolis grew up around St. Anthony Falls; burgeoning flour mills made use of hydropower in the millraces. Over the decades, economic activities on the Mississippi River shifted from agriculture to commerce to tourism and the modern arts. However, in spite of changes through time, the Mississippi River remains a working river: the 9-foot navigational channel is maintained today to River Mile (RM) 857.5, almost to the northern boundary of the MWMO area. Current-day land uses within the MWMO area are mixed urban residential, industrial, and parks. In addition, land uses in the Mississippi watershed above the MWMO, including agriculture, influence the water quality of the Mississippi River within the MWMO. Within the MWMO area, the Mississippi River receives heavy urban and suburban pressures, including industrial and municipal wastewater discharge, recreational use, and stormwater outfalls. According to a recent inventory, there are 324 petroleum leak sites and seventeen sites classified as either state or federal superfund sites (MWMO 2006). The primary mechanism by which these land uses influence the river is storm runoff, which is directed through a network of gutters and conduits to more than eighty stormwater outfalls along the MWMO's reach of the Mississippi River. In addition, most of the shallow groundwater is locally discharged to the Mississippi River (Stark et al. 1999).

Water Uses, Impaired Waters Listings and Lake Pepin TMDL Process

The headwaters of the Mississippi River above Anoka, Minnesota are designated as an Outstanding Resource Value Water (ORVW) and a Wild, Scenic, and Recreational River by the state of Minnesota. In addition, the MWMO reach of the river is part of a National Park unit, the Mississippi National River and Recreational Area (MNRRA). Minnesota Rules 7050.0470 lists the water use classifications for all waters of Minnesota, and the Mississippi River within the MWMO has multiple designations. Above the Upper St. Anthony Falls, the Mississippi River is designated Class 1C (domestic consumption), 2Bd (aquatic life and recreation), and 3B (industrial) waters, protected for drinking water uses due to the municipal water intake for the cities of Minneapolis and St. Paul, which is located at RM 862.8. The lower portion of the Mississippi River within the MWMO is designated Class 2B (aquatic life and recreation), 3B (industrial), 4A (irrigation), 4B (livestock), 5 (aesthetic and navigation), and 6 (upstream of another state) waters. Each of these designated uses has associated water quality standards, summarized in Table 1 for the two reaches, above and below St. Anthony Falls.

Table 1. Selected Minnesota state water quality standards (MnRule 7050.0220), based on water use classifications for reaches of the Mississippi River above and below St. Anthony Falls (SAF) (MnRule 7050.0200). All limits are maximum allowable values, except DO, which is a minimum allowable value, and pH, which is an allowable range of values. NA = not applicable.

Water Quality Parameter	Minnesota Water Quality Standards	
	Above SAF	Below SAF
T (degF)	5 above natural	5 above natural
pH (SU)	6.5 – 9.0	6.5 – 8.5
DO (mg/L)	5	5
SC25 (μmhos/cm)	NA	1000
Turbidity (NTU)	25	25
Hardness (mg/L, as $CaCO_3$)	250	250
HCO_3 (meq/L)	NA	5
Salinity (mg/L)	NA	1000
TDS (mg/L)	NA	700
Na (mg/L)	NA	60% of total cations
Chloride (mg/L)	100	100
HS (mg/L, as S)	NA	0.02
NH_4-N (µg/L)	40	40
Fecal coliform bacteria (#organisms/100mL)	200	200
Mercury (ng/L)	6.9	6.9
PCB (ng/L)	0.029	0.029

The USEPA requires the MPCA to maintain a list of Minnesota waters (any lake, stream reach or river reach) that has been found to exceed the water quality standards of its designated uses (e.g., Table 1). Within MWMO boundaries three reaches of the Mississippi River are on the 2006 Section 303(d) List of Impaired Waters, for aquatic consumption due to mercury and polychlorinated biphenyl (PCB), and for aquatic recreation due to fecal coliform bacteria (Table 2). Table 2 includes the Impaired Waters listings for reaches immediately upstream of the MWMO, as those impairments could have some influence on water quality within the MWMO, short of exceeding the water quality standards. The Impaired Waters listings for reaches immediately downstream of the MWMO are also listed in Table 2. For each pollutant that causes a Minnesota water body to fail to meet state water quality standards, the federal Clean Water Act requires the MPCA to conduct a Total Maximum Daily Load (TMDL) study. TMDL studies set the environmental goals and recommend approaches (implementation plans) for reducing the water quality impairments. One step in the TMDL process is to assign waste load (point source) and load (nonpoint source) allocations to the upstream subwatersheds, and to identify potential pollutant source reductions. In the near future, the MWMO can expect the need to address phosphorus source reductions within the MWMO, due to the Lake Pepin Eutrophication TMDL. Although the Mississippi River Turbidity TMDL has been linked to agricultural runoff from the Minnesota River, the Mississippi River above the Minnesota River (including the MWMO) will be allocated with point and nonpoint source sediment reductions. Although the nutrient phosphorus is the current focus of regulatory agencies, concern has developed about nitrogen as well, since nitrogen concentrations in the Mississippi River are seen as the cause of hypoxia in the Gulf of Mexico.

Table 2. At locations upstream, within, and downstream of the MWMO, the 2006 Minnesota 303(d) Impaired Waters listings, unmet designated water uses, and listed water quality parameters for which standards have been exceeded. (Note: outside of the MWMO, all reaches are listed for Mercury FCA and PCB FCA.)

Listed Reaches	Unmet Water Uses	Listed Parameters
Upstream of the MWMO		
Crow River: So. Fk. Crow R. to Mississippi R.	Aquatic Recreation & Aquatic Life	Fecal coliform Turbidity Fish IBI
Mississippi River: Crow R. to Rum R.	Aquatic Recreation	Fecal coliform
Shingle Creek: Headwaters to Mississippi R.	Aquatic Life	Chloride Low oxygen Invertebrate IBI
Bassett Creek: Medicine Lk. to Mississippi R.	Aquatic Life	Fish IBI
Within the MWMO: Mississippi River segments (in river miles)		
• Coon Cr. to Upper SAF (865-853.9)	Aquatic Consumption & Aquatic Recreation	PCB FCA Mercury FCA Fecal coliform
• Upper SAF to Lower SAF (853.9-853.3)	Aquatic Consumption	PCB FCA Mercury FCA
Lower SAF to L&D#1 (853.3-847.7)	Aquatic Recreation	Fecal coliform Mercury FCA
Downstream of the MWMO		
Miss. River: Minnesota R. to Chippewa R.	Aquatic Life	Turbidity
Lake Pepin	Aquatic Life	Eutrophication (Nutrients)

SAF = St. Anthony Falls
L&D = lock and dam
FCA= fish consumption advisory
PCB = poly-chlorinated biphenyls
IBI = index of biotic integrity

II. Mixing in Big Rivers

Mixing in big rivers is the blending of all inputs to a big river that result in the observed outputs of a big river; the process of mixing usually moves a condition of heterogeneity toward a condition of homogeneity. Under the right circumstances, mixing in big rivers can easily be observed in a mixing boundary. Figure 1 and Figure 2 are dramatic examples of river mixing: at the confluence of the Minnesota River with the Mississippi River at Mendota, MN, and at the confluence of the St. Croix River with the Mississippi River at Prescott, WI, respectively. In the first case, the sediment-rich water of the Minnesota merges with the relatively sediment-poor water of the Mississippi, causing the Mississippi to become sediment enriched. In the second case, the sediment-poor water of the St. Croix merges with the sediment-rich water of the Mississippi. In both cases, the relatively equivalent flow volumes create a mixing boundary that persists far downstream, highly visible due to the stark contrasts in sediment concentrations.

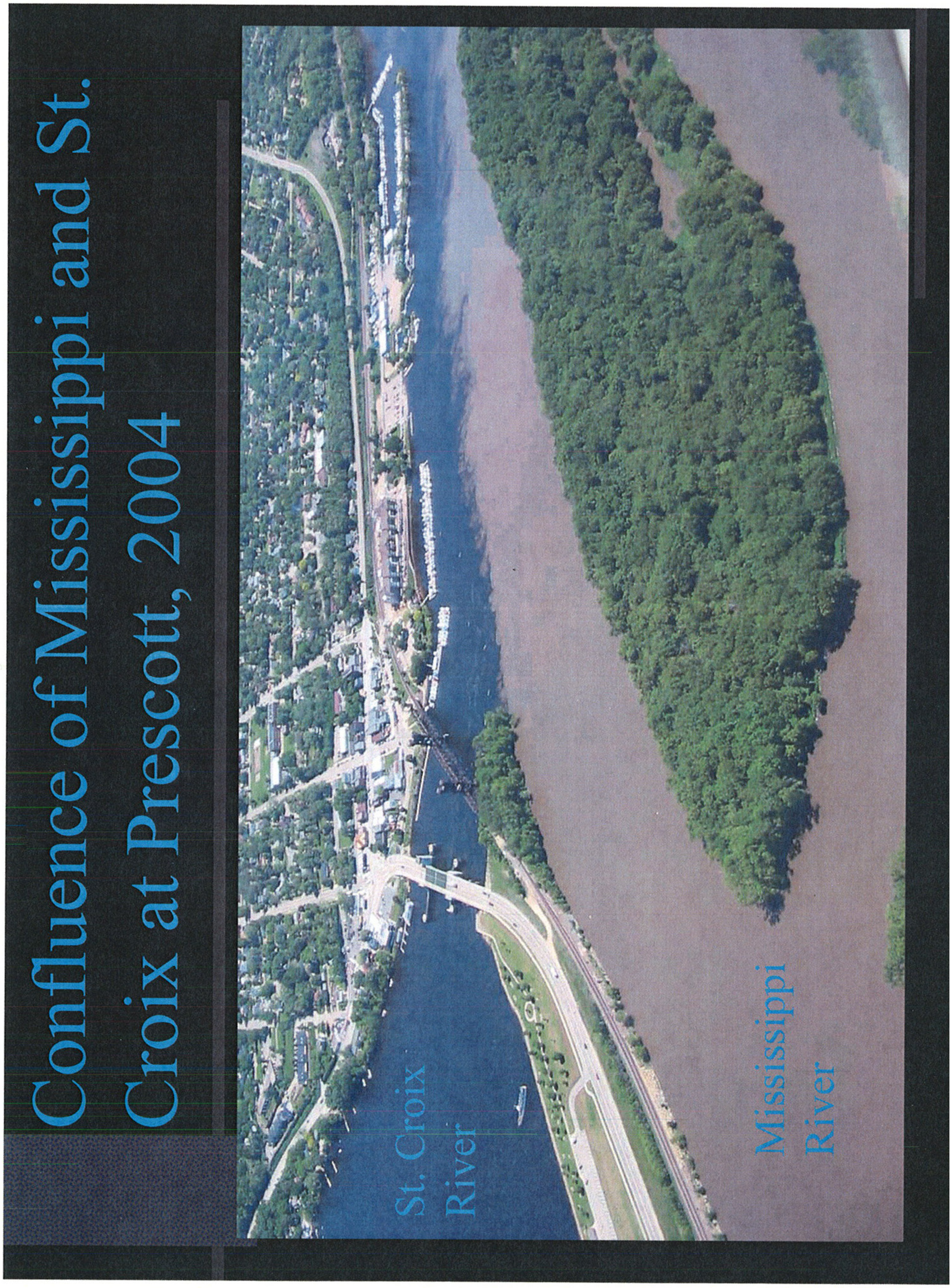

Figure 1: Confluence of the St. Croix River with the Mississippi River at Prescott, WI.

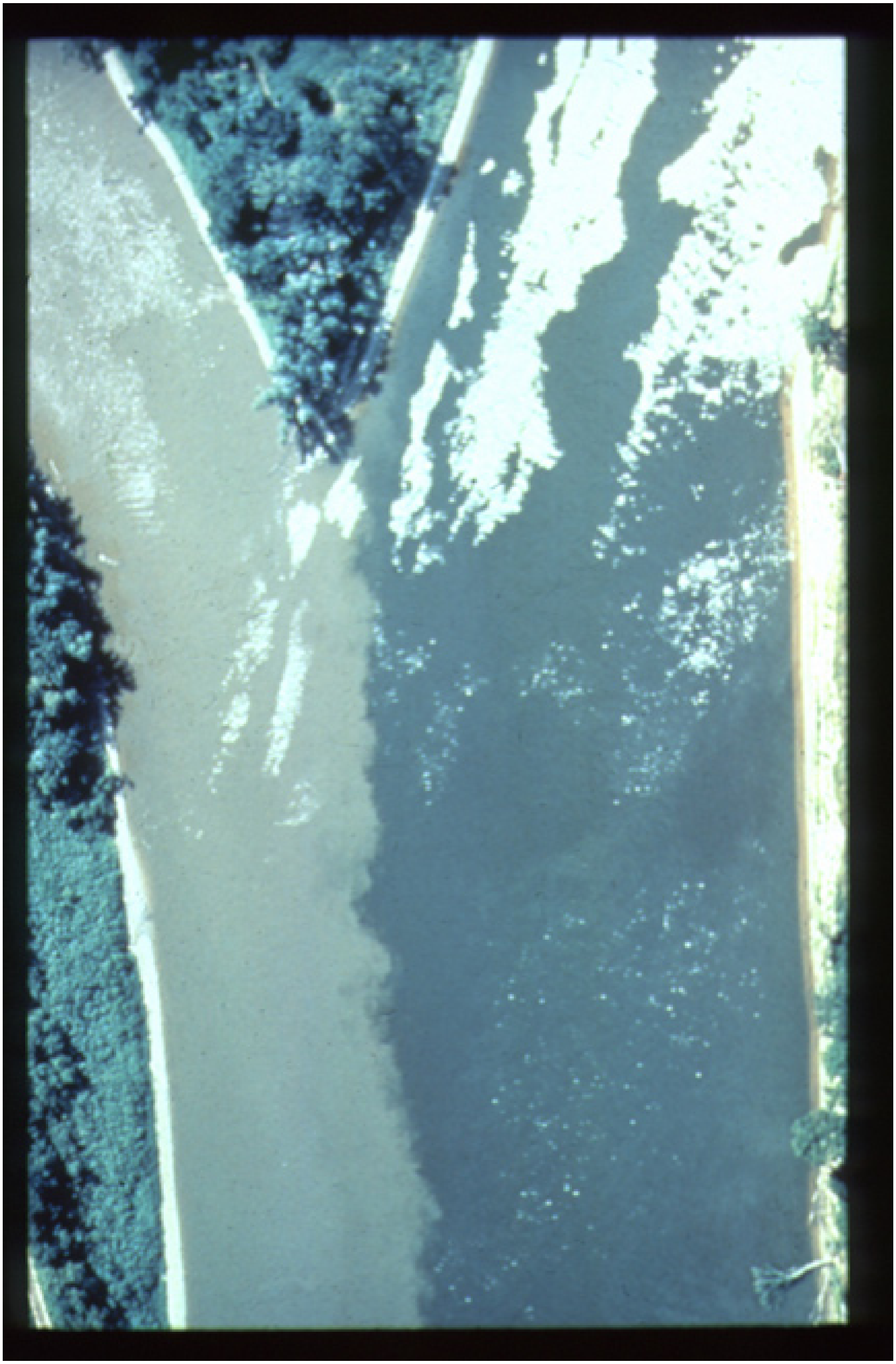

Figure 2: Confluence of the Minnesota River with the Mississippi River at Mendota, MN.

A. Hydraulic and Pollutant Mixing Processes

A big river is not simply a physical phenomenon; the chemistry and biology of a river are active participants in shaping the character of the river. Likewise, river mixing is an integration of physical, chemical, and biological processes. Big river mixing processes are those processes that influence the spatial and temporal distribution of constituents (dissolved or solid) within the water of a big river system. Under ordinary river conditions, each of these processes is occurring at all times to varying degrees. Physical mixing processes often dominate the mixing processes within the main channel of a big river system; only in side channel and backwater areas do physical mixing rates slow down enough for chemical and biological mixing rates to become dominant. The physical mixing processes are the most obvious and fast-acting, visible in the tortuous flow paths of eddies, rapids, and waterfalls. Chemical and biological mixing processes may be less obvious, often slower-acting, but all three types of mixing processes have significant influence on the distribution of constituents within river water and thus water quality. In the following sections, big river mixing processes are grouped into physical, chemical, and biological categories:

Physical Mixing Processes

Physical mixing processes are those hydrodynamic processes resulting from gradients in physical forces (pressure, gravity, etc.), that move molecules within a fluid solution.

Advection

Advection is the passive movement of molecules within a solution due to fluid flow, impelled by force gradients within the fluid.

Hydrodynamic dispersion

The movement of molecules within a fluid due to tortuous flow around solid obstacles or air spaces. Dispersion combined with advection is known as convection. A natural river is constantly in a state of turbulence; turbulent flow occurs when the open-channel hydraulic parameter, the Reynolds number, is less than 500, which will always be the case in a natural river.

Physical mixing occurs in all three spatial dimensions, that is, as vertical mixing with depth, as transverse mixing between river banks, and as longitudinal mixing downstream. To conceptualize physical mixing, it may be helpful to think of the pollutant from the time it is injected until the time at which it is completely mixed in all directions. (The term pollutant is used to describe the parameter of interest, with the understanding it may also be a dye or non-polluting substance.) The time of complete mixing is defined as the time that the pollutant cannot be differentiated from background levels in the river.

Immediately following injection, the pollutant begins to mix in all three spatial dimensions. Mixing is considered complete when measured concentrations are spatially uniform (Putz and Smith 2001). Vertical mixing is completed first, generally within a downstream distance equivalent to 20-100 times the stream depth at the location of injection (Vandenberg et al. 2005). When this occurs, the pollutant is well-mixed in the vertical direction, but mixing still continues in the transverse and longitudinal directions. Transverse mixing is generally completed within a downstream distance equivalent to 100-350 times the stream width at the location of injection (Vandenberg et al. 2005), and can extend 10-100 kilometers downstream (Elhadi et al. 1984). When this occurs, the pollutant is well-mixed in the transverse direction, but mixing still continues in the longitudinal direction. Longitudinal mixing will continue until the point the pollutant is indistinguishable from background concentrations and considered completely mixed.

Chemical Mixing Processes

Chemical mixing processes are those processes that alter the distribution of solutes dissolved in solution. Most of these processes serve to increase the homogeneity of solutes in solution, creating more uniform concentrations of the solute, while some processes increase the heterogeneity of solutes. The following chemical mixing processes can be used to explain the movement of solutes within a fluid solution with a solid substrate interface:

Molecular diffusion

Molecular diffusion is the movement of ions or molecules within a fluid due to randomized vibrations and collisions between molecules (Fischer et al. 1979). This movement typically occurs in the direction of a concentration gradient within the solution, from locations of high concentrations to locations of low concentrations within the solution (Jury et al. 1991).

Adsorption (electrostatic attraction)

The negative charges on the surface of clay minerals or particles of organic matter produce a positive electrostatic attraction for cations (positively-charged ions, like Na^{+}, K^{+}, Ca^{+2}, Mg^{+2}) in solution. Cations are adsorbed onto particles, or retained close to the charged surface by electrostatic attraction, unless they exchange with other cations in solution. In addition, the anion orthophosphate is strongly attracted to calcium ions within cation exchange sites. In this way, the fate of the cation or the phosphate is tied to the fate of the particle ("Whither thou goest, I will go."); it could be carried far from its source, or deposited for an indefinite period in a backwater area.

Precipitation or dissolution reactions

Precipitation reactions are chemical processes resulting in the formation of solids that drop out of a solution, while dissolution reactions are those resulting in the conversion of solid substrate into suspended solutes. The former decreases solute concentrations, while the latter increases solute concentrations. These reactions can be reversible at a later time, under the right circumstances (like evaporation or super-saturation).

Oxidation or reduction reactions

The change in chemical speciation of a molecule due to the gain or loss of electrons. This change is initiated by the presence or absence of electron donors or acceptors (e.g., metals exposed to atmospheric oxygen, or anoxic low-flow conditions in an aquatic resource). The change in chemical speciation (e.g., NO_2^- to NO_3^- to $N_{2(g)}$) can result in different types of transport behavior, trapping compounds in sediments or mobilizing them into solution (Stumm and Morgan 1981).

Biological Mixing Processes

Biological mixing processes are biochemical reactions employed by living organisms that result in alterations to aquatic chemistry. The biological processes most notably involved in aquatic mixing are:

Nutrient uptake

Aquatic plants will consume available nutrients through roots or leaves in order to sustain growth, changing the nutrient composition of their host water. This process is part of nutrient cycling, where nutrients used to build cells are retained within plant tissue for the life cycle of the tissue.

Organic decomposition

Certain microbes (bacteria) employ biochemical reactions to gain energy by decomposing organic matter. These reactions (i.e., respiration, methanogenesis, and nitrate or sulfate reduction) can significantly alter water quality, most notably by over consumption of dissolved oxygen during respiration.

B. Big River Characteristics Affecting Hydraulic and Pollutant Mixing: Summary of Literature Review

Big river characteristics affecting hydraulic and pollutant mixing are those aspects of a big river system that influence the re-distribution of constituents within river water, including those big river characteristics that relate to: 1) point sources of pollutants, 2) the timing of runoff or delivery to the river, and 3) the time of travel within the river system. Characteristics of big rivers that influence mixing were researched and compiled into an annotated bibliography and summary tables (see Appendix A). Across the available literature, the level of detail regarding the effects of big river characteristics on mixing varies from very specific to very general. A minority of the studies specifically discuss the effects of big river characteristics on mixing. In many cases, the effect of a big river characteristic on mixing was not the study's main objective but was discussed in the paper only as an associated issue. In this way, much of the researched material was not focused on mixing in big rivers, but presented a portion of the complete river mixing picture. Many mixing studies are conducted on a very large scale (hundreds of kilometers). These large-scale mixing studies reveal mixing characteristics particular to those river reaches but tend to lump together the effects of many mixing influences, simplifying all mixing characteristics within a reach down to a mixing coefficient.

The characteristics of big rivers that affect either hydraulic or pollutant mixing were organized into four broad categories (physical, chemical, biological, and anthropogenic) and discussed in the following sections. Each characteristic is described according to the findings of the available literature. If papers were not available evaluating the influence of a big river characteristic on either hydraulic mixing or pollutant mixing, it was so noted.

Physical Characteristics

Precipitation

No papers were reviewed that evaluated the influence of annual precipitation on hydraulic mixing in big rivers. However, the volume of annual precipitation determines the volume of surface runoff and groundwater discharge available to recharge a large river system (Stark 1997), and therefore the volume of river water available for hydraulic mixing. Annual variations in precipitation are the primary driver for annual variations in hydraulic mixing due to the resulting low flow or high flow conditions. In addition, rainfall rate across a subwatershed is a key factor in the speed of storm runoff, especially in urban areas where runoff from impervious areas is routed via stormdrain systems into a major river (Ayers et al. 1985, Brown 1984, Payne et al. 1982), short-circuiting pre-development routes of surface runoff. Rainfall and snowmelt often carry low concentrations of total dissolved solids, contributing to pollutant mixing via the dilution of river waters (Fischer et al. 1979).

Elevation

No papers were reviewed that evaluated the influence of elevation or elevation gradient on hydraulic mixing in big rivers. Large rivers tend to be located at lower elevations than smaller streams within the same basin. They also often have shallower elevation gradients than their tributaries and therefore trap more sediment and have longer water retention times (Lubinski 2004). Elevation gradient across a subwatershed is a key factor in the speed of storm runoff (Ayers et al. 1985); steeper slopes cause speedier runoff and delivery to a river, decreasing pollutant time of travel and enhancing mixing where the runoff injects into the river channel.

Flow rate

Higher river flow rates increase the rate of physical mixing processes and decrease pollutant time of travel, i.e., water and pollutants move faster and farther. It has been observed that longitudinal dispersion increases as flow rates increase (Somlyody 1977). River flow rate may be correlated to time of travel if, as flow rates increase, flow velocity increases (Taylor et al. 1985, Jobson 2000). This may or may not be occurring on the Mississippi River and requires further study. Stefan (1982) studied the effect of barge traffic and river flows on vertical mixing in Pool 2 of the Mississippi River. At flows greater than 20,000 cfs, vertical mixing was controlled by river flow rates. At flows between 5,000 and 20,000 cfs, vertical mixing was controlled by a combination of barge traffic and river flow rate. At flows below 5,000 cfs, the vertical mixing in the Mississippi River was controlled by barge traffic.

In contrast to the effect of high flows, lower flow rates decrease the rates of ambient physical mixing processes, allowing chemical and biological processes to dominate (MPCA 2006, MPCA 2005, Lafrancois and Glase 2005, McDonald et al. 2002, Stark 1997), and causing anthropogenic mixing processes to have a greater effect (e.g., Stefan 1982). This is supported by Taylor et al. (1985) who found that during low flow rates, the impact of dams on river mixing can be expected to be greater than at high flows.

Dilution effects are controlled by flow rate and the relative concentrations of effluent and river waters (i.e., concentration gradient). Stefan et al. (1984) investigated the flow from the Metro WWTP during different flow conditions and found that at flows in excess of 30,000 cfs (as measured at the Metro WWTP), the effluent is more quickly diluted although it remains close to the near bank as a vertically-mixed transversely-spreading plume. At lower flows, the plume remains vertically stratified for several miles downstream.

Seasonal and daily extremes of drought and flooding

Flow extremes result from imbalances between water availability (rainfall or snowmelt) and water uptake (the growing season of plants and storage in reservoirs). Midwestern rivers exhibit a common seasonal pattern of high flows in the springtime and low flows in late summer. Impervious areas influence this seasonal pattern by enhancing speedy runoff for storms throughout the summer, while pervious agricultural lands are affected by the dominance of plant uptake during the growing season, which reduces runoff rates after canopy closure (Fallon and McNellis 2000). Seasonal extremes have been shown to create different pollutant attenuation characteristics (Fallon and Chaplin 2001). For example, wastewater treatment plant (WWTP) effluent discharged to the Bow River in Calgary exhibited much more nitrate uptake by macrophytes during low-flow conditions in October when compared to high-flow conditions in April (Vandenberg 2005). Additionally it can be said that mixing varies greatly between seasons despite flow conditions, indicating different mixing characteristics throughout the season (Vandenberg 2005). Seasonal high flow periods can deliver excessive amounts of sediments to a river system, altering mixing patterns and reducing flood capacity (Zhang et al 1999). Seasonal extremes in flow volume affect pollutant concentrations (e.g., dilution or concentration). Changes in water quality mass balances may initiate chemical dissolution/precipitation reactions, such that pollutants are either stored in sediments or released from sediments into the water (e.g., low-flow anoxic conditions).

Tributaries

Surface runoff via tributary streams provides direct pathways for water and pollutants to reach a big river (Lubinski 2004, Magdalene et al 2007, McDonald et al. 2002, MetC 2005, Oakley et al. 2003, Payne et al. 1982, Stark et al. 1999, Zhang et al. 1999). The water quality of a tributary could be very different than the water quality of a big river, depending on land use patterns and point sources in the subwatershed (MPCA 2006, MPCA 2005, MPCA 2004, MPCA 2003, Stevens and Olsen 2004, Kloiber 2004, Kroening 1998, Engstrom and Almendinger 1998, Gilliom et al. 1995). The length of the mixing zone within the mainstem river can be significant, depending on the ratio between tributary and river flow volumes at the mouth of the tributary. For example, samples taken downstream of a major tributary to the Athabasca River showed evidence of a dilution effect that persisted 13.5 km downstream (Putz and Smith 2001).

Groundwater discharges

Groundwater discharge to surface waters is that portion of the water cycle that infiltrates into the subsurface and is not captured by root uptake; groundwater flow through the subsurface can take hours to centuries before reaching a point of discharge. Groundwater discharge to a large river system provides the baseflow portion of river discharge, or that minimum flow level that sustains the river during dry spells (Gilliom et al. 1995). While these flows carry little momentum, they can affect river compositions (Payne 1995). During drought periods (i.e., the upper Midwest in the late 1980s), groundwater seepage into surface waters has a larger influence on pollutant mixing than during wet periods (Lafrancois and Glase 2005). The composition of groundwater flows depends on the land use and contamination sources within the contributing area (Stark et al. 1999). For example, contamination from pesticides and nitrates in the highest susceptibility surficial aquifers appear to be associated with human activities within the contributing area (Hansen 1998). Pollutants representing different land uses are differentially transported through groundwater systems and discharged to major rivers

(Hansen 1998, Fong 2000). Capel et al. (1998) recommend sampling for pesticides in streams and rivers during baseflow, since little of the load is delivered by stormflow.

River channel morphology

River channel morphology can have an impact on the mixing in big rivers, and meanders affect the dispersive characteristics of a stream reach (Lee 1995). Wide and slow channels (i.e., large navigational pools or riverine lakes) may stratify with respect to temperature or dissolved oxygen, which inhibits vertical mixing and controls the distribution of aquatic organisms, which further influence mixing (Soballe and Fischer 2004, Talmadge et al. 2000, Goldstein et al. 1999, Holland 1986). If the cross sectional area increases in a reach with increasing flow the advection rate may remain constant, which contributes to keeping the longitudinal dispersion constant (Caplow et al. 2004). For rivers over 200 meters wide, equations by Lau and Fischer overestimate the longitudinal dispersion coefficient (Seo and Cheong 1998).

Greater channel sinuosity enhances lateral mixing (Kloiber 2003); the sinuosity of a river plays an important role in determining the value of mixing coefficients (Lau 1985). Meanders change the mixing characteristics by creating secondary currents and causing portions of the flow to lag (Baek et al. 2006). In the case of meandering rivers, the pollutant primarily remains on the side of the stream that it was injected throughout at least two meanders (Baek et al. 2006). Additionally, pollutants in the middle of a river may split into two separate pollutant clouds by the combined action of secondary currents and non-uniform primary current during a meander cycle. Channel sinuosity can enhance sediment transport and substrate grain size sorting through streambank erosion at cutbanks, increasing sediment loading to the river, while deposition occurs at slow spots like point bars inside the meander bends (Chick et al. 2005, USACE 1995). A meandering channel has a continually changing rate of transverse mixing throughout its meander cycle (Boxall and Guymer 2003). Also at river bends, using a depth-average mixing assumption is unacceptable. This indicates that a depth average assumption may be too general for most situations unless the river is very shallow and flows are very turbulent (Demetracopoulos 1994).

River islands

The only hydraulic mixing paper to address islands (Rathbun and Rostad 2004) examines a river reach with islands and a sharp bend. This makes determination of the exact impact of the islands difficult, but it can be inferred from the larger lateral mixing coefficients in rivers with islands (Rathbun and Rostad 2004) that islands increase the lateral mixing in big rivers. No papers were reviewed that evaluated the influence of river islands on pollutant mixing in big rivers.

Ice cover, flows, and blockages

The presence of ice cover in a stream alters the flow characteristics of the river. The turbulence increases due to increased resistance resulting from an additional solid boundary and average flow velocity decreases. Additionally, both the velocity and shear stress distributions change, which can either increase or decrease the mixing coefficients (Lau 1985, Lau and Krishnappan 1981). In situations where a flow of cooling water enters the river under ice cover, the ice cover eliminates surface currents in the river and the effluent can develop a surface spreading pattern near the outlet more easily (Stefan et al. 1976). Ice cover also has the potential to create seasonal anoxic conditions beneath the ice cover (Soballe and Fischer 2004).

Wind

Wind enhances physical mixing in the surface layers of water resources. Wind could contribute to mixing at flows in the Mississippi River less than 5000 cfs, but is negligible at higher flows (Stefan 1982, Thene and Wang 2002, Voight and Kostic 1998). The density of a pollutant medium relative to the density of river water influences whether it floats or sinks, and hence its degree of mixing within the river. An oil slick will move based primarily on the surface velocity of the water and the direction and magnitude of the wind (Hibbs et al. 1999). No significant wind impacts were detected during a mixing study on the Mississippi River at Monticello (Stefan et al. 1976). No papers were reviewed that evaluated the influence of wind on pollutant mixing in big rivers. Significant research has been conducted on the effect of wind on water movement and mixing in the direction of wind fetch within lakes. Wind mixing in rivers should behave much differently, depending on whether channelized flow aligns with the prevailing winds or not.

Dead zones

Dead zones are areas of low to zero flow, which occur in backwater areas and secondary channels. Physical mixing processes are dampened and pollutant time of travel increases; dead zones can cause a lag in the downstream progression of pollutants. It has been demonstrated in laboratory experiments that, where dead zones exist, a longitudinal concentration distribution of an instantaneously injected pollutant will be a low-peak, long duration curve, indicating that pollutants become trapped and slowly released to the main course of water over an extended period of time (Beltaos and Arora 1988). Very little mixing occurs between dead zones and the rest of the river and this can allow very steep concentration gradients to exist between them. No papers were reviewed that evaluated the influence of dead zones on pollutant mixing in big rivers.

Chemical Characteristics

Field conditions (temperature, etc.)

Ambient field conditions of river water (temperature, pH, specific conductance, dissolved oxygen) influence and are influenced by hydraulic mixing processes. Mixing of dissolved oxygen (DO) into agitated river water is partially controlled by ambient temperatures: summer heat, lower flow levels, and biological consumption collude to cause minimum DO concentrations in late summer (MPCA 2003, Oakley et al. 2003, Ayers et al. 1985). Heated effluent entering a river at ambient temperatures causes the effluent to dive or float depending on the season, i.e., whether the effluent is hotter or colder than ambient temperatures. For example, during a study of effluent discharge to the Mississippi River at the Monticello power plant, a rising plume was detected during the winter, while a diving plume was detected during the summer (Stefan and Gulliver 1978).

Thermal stratification inhibits vertical mixing. Under low discharge rates an unmixed wedge of cold water can form in an outlet channel, indicating that the water is not vertically well-mixed due to temperature gradation. Enhanced lateral surface spreading caused by the buoyancy of warm water effluent is apparent by tilted isotherms near the outlet of the Monticello power plant (Stefan et al. 1976). Decreased temperature and increased dissolved solids of an effluent plume increases vertical stratification in a river. In this case, the colder water sinks to the bottom and is not present at the surface until further downstream (Stefan 1982). Thermal stratification influences the distribution of biological organisms, which further influence mixing through biochemical exchanges and physical disturbance of the substrate (Chick et al. 2005, McDonald et al. 2002, Stevens and Olsen 2004, Goldstein et al. 1999).

Pollutant properties

The properties of a pollutant and its medium can affect its mixing rate and time of travel (Lafrancois and Glase 2005, MDH 2001). One factor in pesticide detection frequencies is pesticide type; pesticides are semi-volatile organic compounds, some of which persist longer in surface water than other types (Fallon 2000). Trace metals and hydrophobic compounds like polychlorinated biphenyls (PCBs) tend to resist decomposition and persist in the natural environment, accumulating in sediments and fish tissue, rather than water (Kroening et al. 2000, Stark et al. 1999, Lee and Anderson 1998). The density of a pollutant medium relative to the density of river water influences whether it floats or sinks, and hence its degree of mixing within the river. An oil slick will move based primarily on the surface velocity of the water and the direction and magnitude of the wind (Hibbs et al. 1999). The saturation, concentration, and dissolution rate of the oil are the most important factors to determining aqueous concentration and the impact on river biota (Hibbs and Gulliver 1999b).

Substrate properties

No papers were reviewed that evaluated the influence of substrate properties on hydraulic mixing in big rivers. However, the particle size distribution of substrates in the river bed can influence the mixing rates of certain pollutants (Fallon 2000, USACE 1995, Holland 1986). Clay and silt sediments can serve as cation adsorption sites for a variety of chemical compounds including phosphorus and hydrocarbons. This can either: 1) delay pollutant transport indefinitely, when deposited at a backwater location, until the compounds are again released into circulation (e.g., anoxic conditions during a drought), or 2) enhance transport of a compound far from its source. For example, sediment dynamics within a large river influence phosphorus transport within and through the river reach (James 2006). Excess sedimentation in reservoirs and backwaters can reduce habitat and inhibit aquatic plant growth, decreasing biological uptake of nutrients, thereby expanding the travel time and distance of compounds that might have been consumed in cell growth (Flotemersch et al. 2006, Chick et al. 2005, Talmadge et al. 2000, Goldstein et al. 1999).

Suspended solids and sediment

No papers were reviewed that evaluated the influence of suspended solids on hydraulic mixing in big rivers. Solid particles in the water column will settle-out or deposit, depending on their density, size, and the velocity of flow; higher flows can carry more sediment mass (USACE 1995, Ayers et al. 1985). Smaller solid particles held in suspension in the water column inhibit light penetration, reducing primary production of algae and other biological mixing processes, increasing travel time and distance of certain pollutants (Zhang et al. 1999). Fine-grained sediments (clay and silt) can transport phosphorus long distances from its source (Engstrom and Almendinger 1998, James 2006, MPCA 2003, 2004, 2005, 2006).

Nutrient cycling

No papers were reviewed that evaluated the influence of nutrient cycling on hydraulic mixing in big rivers. Seasonal inputs of plant nutrients in surface runoff do not always coincide with the timing of the seasonal uptake of nutrients (Ayers et al. 1985). Phosphorus can be trapped in sediments to be released at a later date (James 2006), while nitrogen is quite mobile (Hanson 1998, Magdalene et al. 2007, MDH 2001, Stevens and Olsen 2004, MPCA 2004, 2005, 2006). Excess nutrients can promote the growth of phytoplankton and increasing numbers of planktivores (Flotemersch et al. 2006, Goldstein et al. 1999). If not consumed by algae, nitrogen can be transported far downstream to the Gulf of Mexico (Kroening 1998, Engstrom and Almendinger 1998).

Biological Characteristics

Riparian vegetation

No papers were reviewed that evaluated the influence of riparian vegetation on hydraulic mixing in big rivers. Riparian vegetation tends to reduce streambank erosion through bank stabilization (Lafrancois and Glase 2005, ZumBerge, Perry, and Lee 2003). In addition, it can reduce suspended sediment concentrations (through streambank roughness) and reduce nutrients (through plant uptake) (Kloiber 2003). Overhanging and rooted vegetation can create aquatic habitat (Chick et al. 2005) and inhibit warming (Talmadge et al. 2000, Goldstein et al. 1999).

Primary productivity

No papers were reviewed that evaluated the influence of primary productivity on hydraulic mixing in big rivers. Primary productivity refers to the local photosynthesis that occurs during aquatic plant growth, whether submerged, emergent, or floating. With sufficient light penetration, plant cell growth of primary production can reduce nutrient concentrations in river water, reducing travel times and distances. However, these aquatic plants are rarely harvested, and the nutrients will eventually return to the river as plant tissues break down. If there is too much primary production at one time, the subsequent die-off consumes available oxygen and can cause anoxic conditions near the river bed, stressing aquatic organisms and contributing to eutrophication that may be difficult to reverse (Soballe and Fischer 2004).

Anthropogenic Characteristics

Stormwater outfalls

Stormwater outfalls allow anthropogenic chemicals to be washed from an anthropogenic landscape, by way of an anthropogenic conduit, to the river (Ledder 2003). Constructed for the efficient removal of storm runoff from urban impervious surfaces, stormwater outfalls impact mixing in the same way as tributaries by introducing pollutants and dynamic flows to the river (Ayers et al. 1985, Payne et al. 1982). Due to smaller relative volumes, stormwater outfalls usually have a much smaller mixing zone than tributaries, but can carry substantial momentum into receiving waters (Lau and Krishnappan 1981). In nearby downstream areas, some urban pollutants are persistent in fish tissue and streambed sediments for decades, mixing with river water in time (Kroening et al. 2000).

Private and industrial outfalls

Although private and industrial outfalls occur at unknown flow volumes and frequencies, the monthly flow volume and average pollutant concentrations in the discharge must be reported to the MPCA through the NPDES permit program. These outfalls generally impact mixing by discharging relatively high concentrations of pollutants to the river. The transverse mixing of effluent is generally slow unless the outfall discharge has a large initial momentum. The mixing zone is also affected by the orientation of the outfall to the normal flow direction of the river. There are methods to determine the exact mixing zone of small effluent discharges entering the river, but this requires much site-specific data (Stefan and Gulliver 1978). In nearby downstream areas, some urban pollutants are persistent in fish tissue and streambed sediments for decades, mixing with river water in time (Kroening et al. 2000). In the densely populated Twin Cities Metropolitan Area, the geographic distribution of polychlorinated biphenyls (PCB) concentrations in common carp and walleye correspond with the location of historical point and nonpoint source PCB inputs (Lee and Anderson 1998).

Wastewater treatment plants

Wastewater treatment plants (WWTPs) are a major source of pollutants to an urban river (Ledder 2003); improvements in wastewater treatment technologies can improve degraded water quality (Kloiber 2004) while population growth can further stress it (Metropolitan Council 2005). WWTPs promote mixing in rivers through jet effects and displacement effects. Jet effects are the mixing and turbulence caused by the momentum of the incoming effluent. In the nearfield (at and just downstream of injection), jet effects are a major component of mixing (Voigt and Kostic 1998). In a study of the Metro WWTP, the outlet channel widens considerably at the confluence with the Mississippi River, reducing the jet effects to negligible levels (Stefan 1982). The displacement effect must be accounted for when a large mass of effluent is injected into stream flow. That is, as effluent is injected into stream flow, the river water flowing past is pushed away from the effluent injection point. The effect of the additional wastewater input and the downstream wastewater plume composition can be described by using a CORMIX model (Thene and Wang 2002). When investigating the mixing zone of a WWTP, temperature or conductivity and chloride have been used as sampling indicators to measure effluent mixing (Vandenberg et al. 2005).

Land use and land cover of contributing area

No papers were reviewed that evaluated the influence of land use or land cover of contributing areas on hydraulic mixing in big rivers. The land use and land cover of a river's contributing area affects both quantity and quality of surface runoff to streams and rivers and therefore influences big river mixing zones (Magdalene et al. 2007, Lubinski 2004, Soballe and Fischer 2004, MDH 2001, Fallon and McNellis 2000, Talmadge et al. 2000, Stark et al. 1999, Gilliom et al. 1995, Brown 1984). Forests and wetlands tend to release less dynamic runoff with low pollutant concentrations (Fallon 2000), while urban areas with more impervious surfaces tend to release more dynamic runoff with relatively higher pollutant concentrations (Kloiber 2004, Ledder 2003, ZumBerge, Perry and Lee 2003, Engstrom and Almendinger 1998). Urban land uses, combined with efficient drainage to rivers, cause higher concentrations of trace elements in river water and sediments, which subsequently persist within and downstream of urban areas (MPCA 2006, 2005, Metropolitan Council 2005, Kloiber 2003, Kroening et al. 2000, Stark 1997). Agricultural lands with exposed soils and fast drainage tend to release flashier runoff with high concentrations of sediments and nutrients (Fallon and McNellis 2000, Kroening 1998). In the highest susceptibility surficial aquifers that recharge streams and rivers, contamination by pollutants appears to be associated with human activities in the contributing area (Fallon and Chaplin 2001, Hansen 1998). Human perturbations reduce the water and soil conservation ability of watersheds, resulting in siltation of riverine impoundments and channels, thereby reducing flood capacity and travel times (Zhang et al. 1999).

Water appropriations

Although no papers were reviewed that evaluated the influence of water appropriations on hydraulic mixing in big rivers, many of the mixing studies that contain information regarding longitudinal dispersion coefficients were conducted to estimate travel times of spills upstream of drinking water supplies (Kloiber 2003, MDH 2001). These studies are site specific and the mixing coefficients found through those studies can not be applied to other rivers.

Vessel traffic

Vertical mixing of a stratified river is accomplished effectively by barge traffic and may be the main vertical mixing process under low-flow conditions. Under low river flow conditions the lateral displacement of the water by a barge tow and the return flow after the passage causes almost immediate mixing (Voigt and Kostic 1998). Stefan (1982) found that on Pool 2 of the Mississippi River, three passes of tug boats appear sufficient to vertically mix the river. Recreational vessel traffic may impact river mixing also but literature was not available to quantify the effect. According to Holland (1986), barge traffic caused significant short-term changes in spatial distribution of ichthyoplankton eggs and larvae, and caused significant physical damage to eggs, but not to larvae or small fish. Vessel traffic is one of the anthropogenic stressors that influence pollutant mixing and time of travel in large rivers (Lubinski 2004).

Locks-and-dams

Lock-and-dam structures are installed to enhance navigation by permanently raising river stage, creating an artificial riverine lake in the lower reaches of the pool (Zhang et al. 1999). At low to moderate river discharges, water elevation in pooled reaches of the Upper Mississippi is controlled by dam operations, while at high discharges, all gates in the dams are opened completely, and water elevations are a function of discharge volume and river topography (Soballe and Fischer 2004). The effect of mixing at the dams in the Potomac River in Maryland was most pronounced at low river discharges, and less pronounced at high discharge, indicating that at low flows the dams play a significant role in the river's mixing, while under high flows the river mixing is controlled by other factors (Taylor et al. 1985). Dams and navigational pools reduce the rate of longitudinal dispersion when compared to un-dammed rivers with similar flow rates (Caplow et al. 2004). Dams may be useful when conducting tracer experiments by enabling the researcher to manipulate flow rates (Pujol and Sanchez-Cabeza 2000)

In Minneapolis/St. Paul, the Mississippi River retains a significant amount of TSS, through sedimentation in the quiescent pools created by the lock and dam system (Kloiber 2004, USACE 1995, Stark 1997). Pollutants or sediments can become trapped behind locks, and will occur as slow leakage from the lock sediments or as a slug of pollutant concentration when the lock is drained. Localized photosynthesis (primary productivity) in large rivers is limited by turbid water. However, the presence of dams, floodplains with large backwaters, or large amounts of woody debris in a given large river reach can reset energy processes to conditions more like those that occur in moderate size streams (Lubinski 2004). Dams create a physical barrier to migration of biological organisms: 70 species of fish have been identified above St. Anthony Falls in Minneapolis, and about 120 species below the falls (Goldstein et al. 1999, Stark 1997).

Wing dams

Wingdam structures are installed perpendicular to streambanks, thereby reducing erosion by deflecting flow away from the streambank. Wingdams were not explicitly investigated in any of the literature reviewed, but Stefan (1982) offers that an alternating series of wingdams will have an impact on the transverse mixing coefficient. No papers were reviewed that evaluated the influence of wing dams on pollutant mixing in big rivers.

Bridge piers

Although no papers were reviewed that discussed the influence of bridge piers on mixing, the easily visible turbulence around bridge piers can be expected to influence big river mixing processes (USACE 1995). Bridge piers are an especially important consideration if the bridge will be used for sampling access, particularly if a bridge pier happens to interfere with the centroid of flow.

Weirs

Weirs are small dams created in rivers. Weirs result in increased settling of solids upstream and the accumulation of oil and grease downstream (Stefan and Johnson 1987). Weirs can cause a dead zone to form upstream of the structure and impact mixing as discussed under that heading. No papers were reviewed that evaluated the influence of weirs on pollutant mixing in big rivers.

Summary of Mixing Influences and Outcomes

Big rivers are significantly different from the tributary streams that feed them; they have shallower elevation gradients than their tributaries and therefore trap more sediment and have longer water retention times (Lubinski 2004). Variability in weather conditions and the geometry of drainage slopes, pipes, and channels, and of flow obstructions are the primary physical drivers for mixing behavior in big river systems. In addition, chemical, biological, and anthropogenic characteristics of a big river collaborate to influence the complexities of mixing behavior observed in big river systems. For example:

- Stratification of water layers causing oxygen concentrations <1.0 mg/L are not frequently encountered in routine sampling. However, these conditions do occur in the Upper Mississippi, particularly under ice cover in the northern reaches, in the vicinity of groundwater inflow, in dense beds of submersed aquatic vegetation, and in deep, stagnant, areas with high sediment oxygen demand (Soballe and Fischer 2004).
- Early spring rains on accumulated snowfall can create a flood of dilute waters, while early summer thunderstorms prior to canopy closure can flush sediments and nutrients from an agricultural landscape.
- The low river flows at the peak of the growing season in late summer are ideal conditions for primary productivity; algal blooms can consume dissolved oxygen down to the level that pollutants may be released from sediments due to anoxic conditions close to the riverbed.

C. Reaches Within the MWMO

The big river mixing characteristics of the Mississippi River, especially channel morphology, change as the river flows through the MWMO. At the upstream boundary of the MWMO, the Mississippi is a free flowing channel draining northern hardwood forests and agricultural areas. As the Mississippi flows through the MWMO, it becomes the first two “stair-steps” of the USACE navigational pool system in the Upper Mississippi River basin. Mixing reaches of the Mississippi River within the MWMO were delineated based on the ability to correlate monitoring data between the reaches and changing flow conditions in the river. A longitudinal profile of the Mississippi River (Appendix B) created by FEMA for a flood insurance study was used to help select the boundaries between four mixing reaches. The reaches are indicated by reach numbers outside the border on the bottom of the page in Appendix B and on the fold-out map Appendix C. It is helpful to discuss the river mixing in the MWMO by reach, as the mixing zones and monitoring protocols change throughout the MWMO.

Reach #1 (RM 859.0 –RM 857.8): 53rd Ave. N. to Bridge at 42nd Ave N./37th Ave. N.E.

The first reach is the only free-flowing stretch of the Mississippi within the MWMO. The reach is delineated by the extent of the MWMO on the north end to the location where the river takes on the characteristics of the Upper St. Anthony Falls reservoir. Appendix B shows the longitudinal profile of the river at the downstream delineation. The break from free-flowing to impounded water is shown as the divide between Reach 1 and Reach 2. The surface area of this free flowing river reach is approximately 0.38 km^2 (94 ac).

Reach #2 (RM 857.8 –RM 854.1): Upper St. Anthony Falls Pool

The second reach extends from the bridge at 42nd Ave N./37th Ave. N.E. to the Upper Saint Anthony Falls Dam. The most upstream impoundment of the USACE navigational pool system is the Upper Saint Anthony Falls Dam. This reach is characterized as a navigational pool and channel and has a surface area of 1.45 km^2 (358 ac), and its channel is set within a low-cut bedrock gorge.

Reach #3 (RM 854.1 – RM 853.4): Lower St. Anthony Falls Pool

The third reach encompasses the Upper Saint Anthony Falls Dam to Lower Saint Anthony Falls Dam. This reach is a navigational pool and channel with a surface area of 0.2 km^2 (50 ac); it is a channel incised within a bedrock gorge.

Reach #4 (RM 853.4 – RM 847.6): Lock and Dam #1 Pool

The fourth reach extends from Lower Saint Anthony Falls Dam to the MWMO downstream boundary near the Ford Dam (LD #1). This reach is characterized as a navigational pool having a surface area of 2.1 km^2 (525 ac), with its channel incised within a bedrock gorge. This reach extends 5.8 river miles downstream from lower St. Anthony Falls Lock and Dam to the southern boundary of the MWMO.

D. Description and Influence of Big River Characteristics on Mixing Within Each Reach

The following descriptions attempt to identify the major components of mixing within each reach of the MWMO as described in the previous section. In many cases, the literature supports that a characteristic will have an influence on mixing but site specific data is required to identify and quantify the effect. Where more site-specific mixing data is required to identify the impact of a characteristic, it may be obtained through the techniques explained in Section V.

All Four Mixing Reaches

The following big river characteristics have mixing influences that apply to all four MWMO reaches: 1) in relatively uniform distribution, remaining consistent, even constant, along all four mixing reaches, 2) in unknown distribution, or 3) not at all.

1. Relatively Uniform Distribution within the MWMO

Precipitation

Rainfall between the reaches is considered constant although it is recognized that precipitation can vary dramatically over very short distances. For this reason it is recommended that a dense rainfall gauge network be constructed to accompany any monitoring program. Please see the previous description of the impacts of precipitation.

Seasonal and daily extremes of drought and flooding

The MWMO area is a small enough drainage area that seasonal averages in precipitation will tend to average-out, lending consistency to the spatial distribution of surface runoff. The entire MWMO area should experience similar extremes in drought and flooding. The monthly average flow ranges from 5,330 cfs to 20,200 cfs at Lock and Dam #1. The historical peak flow of 91,000 cfs was recorded on April 17, 1965, while the lowest recorded flow was 602 cfs on August 29, 1976 (USACE 2004b).

Groundwater discharge

Groundwater discharges to the MWMO have not been adequately quantified to assign discharges to each reach. In winter, groundwater springs are most visible on the north and east facing bluffs of the Mississippi, as large ice cliffs which persist into springtime. Payne (1995) provides an estimate of 2.59 cubic feet per second (cfs) per river mile in the reach of the Mississippi River from Fort Ripley to Anoka, MN. Payne does not offer any insight as to whether or not this estimate would apply downstream of this reach. It is unknown to what degree groundwater chemistry influences big river mixing processes,

Land use and land cover of contributing area

Although the land use of individual subwatersheds within the MWMO is variable, the overall urban land use and land cover of the contributing area (or watershed) of any given river monitoring location do not vary significantly throughout the MWMO reach of the Mississippi River. Thus, individual stormwater outfall monitoring sites could represent very different land uses and land covers, but the Mississippi River monitoring sites will represent similar land use distributions since the MWMO is a small proportion of the contributing area for any of these sites. The surrounding area is primarily a mixture of highly impervious urban industrial, urban residential, transportation corridors, and parklands, with a slightly greater concentration of impervious surfaces near downtown Minneapolis (parts of Reaches #2-4). Although agricultural lands comprise a significant portion of the watershed above the Twin Cities Metropolitan Area, the proportional influence on river water quality of those agricultural lands diminishes as the river enters the urban area.

2. Unknown Distribution within the MWMO

River flow rate

Long-term flow gaging of the Mississippi River has not occurred within the MWMO area, and the distribution of flow rates across the MWMO is unknown. The nearest upstream long-term flow gage on the Mississippi is six miles upstream near Anoka, MN (USGS gage #05288500), and the nearest downstream long-term flow gage on the Mississippi is nine miles downstream at St. Paul, MN (USGS gage #05331000), located downstream of the confluence of the Minnesota River with the Mississippi. Subtracting the flows of the Minnesota River at Jordan, MN, the difference between Anoka and St. Paul in the historical flow record has ranged from +92 cfs in 1935 to +1160 cfs in 1986. The origins of flow and changes in flow rate between the reaches could be further analyzed by undertaking a study of flow sources. More information on a potential flow study is provided in Section V.

Ice cover

Even a big river is at least partially frozen over in winter, with flow occurring beneath the ice. No data was recovered during the literature review that discussed ice cover particular to the reaches of the MWMO. Ice cover does have an impact on hydraulic mixing and water quality, and should be noted during sampling when present.

Wind

The influence of wind on the mixing of the Mississippi River within the MWMO area is not documented. It is expected that this effect should vary as the Mississippi meanders through the MWMO area, changing its orientation to the direction of prevailing winds.

Stormwater outfalls

Over eighty stormwater outfalls are located along the Mississippi River within the MWMO watershed; their exact locations and relative influence on each reach (e.g., volume outflow or pollutant mass per river mile) need to be verified by the MWMO. Stormwater outfalls 36″ or larger are shown on the reach map (Appendix C) included in this report. Stormwater outfalls can cause a skewed data set if water is sampled too near the outfall. Further information on outfalls can be found in the previous section under Anthropogenic Characteristics.

Field parameters

The highest frequency sampling of these parameters occurs weekly at the MCES sites on the MWMO boundaries (at RM 863 and RM 848), but detailed information about the spatial distribution of field parameters throughout the MWMO reaches is not available. An expected influence of the reservoir conditions in these reaches would be to slow down flow rates and allow greater warming of reservoir waters.

Suspended sediments, nutrient cycling, and primary productivity

The spatial distribution of the influence of suspended solids, nutrients, and biota is also unknown for the MWMO reaches. An expected effect of the reservoir conditions in these reaches would be to decrease suspended solids as sediments settle within the reservoir basins, improving clarity and light penetration so that more nutrients are consumed in primary productivity.

Pollutant properties

While the influence of individual pollutants on mixing has been evaluated, the documentation of the distribution of these pollutants throughout the MWMO area is incomplete. Ideally, a review of historical sampling data should be tied to a GIS-database.

Substrate properties

It is unknown whether the distribution of riverbed substrates has been documented throughout the MWMO, and how these distributions change with time. Some information may be available from the extensive, but not digital, collection of reports by the USACE.

Riparian vegetation

Studies of riparian vegetation along the Mississippi River corridor have been conducted (e.g., Kloiber 2003), but it is unknown how these distributions influence mixing within the MWMO.

3. Do Not Occur Within the MWMO

The following river characteristics do not occur within the MWMO and are not described in further detail as they relate to mixing in the MWMO reaches.

- WWTPs
- Wing dams
- Weirs

The following descriptions of big river characteristics that affect mixing within individual reaches are summarized at the end of the section in Table 3.

Reach #1 (RM 859.0 – RM 857.8): 53rd Ave. N. to Bridge at 42nd Ave N./37th Ave. N.E.

Elevation

This reach is upstream of the bedrock gorge through which the Mississippi River flows in Minneapolis and St. Paul. The riverbanks and surrounding lands are about 40 to 45 feet above the elevation of the river.

Tributaries

Shingle Creek enters at the bottom of the reach at RM 857.9 just above the bridge and drains approximately 175 km^2 (67.5 mi^2) (Shingle Creek Watershed Management Plan 2004). The creek has an average annual discharge rate ranging from 0.34-0.85 cms (12-30 cfs), with a median value of 0.48 cms (17 cfs) for the years 1996-2006 as recorded by USGS station #05288705. The monthly discharge rate within the period of record varied from 0 in January 2004 to 1.67 cms (59 cfs) in July 2002. The lowest average monthly discharge rate of 0.11 cms (4 cfs) occurs in January and the highest average monthly discharge rate of 0.91 cms (32 cfs) occurs in May and June. The inflow of Shingle Creek will have the effect of displacing Mississippi River flow toward the east bank as it mixes with the Mississippi River.

Industrial outfalls

The Minneapolis Water Works has three NPDES permits for outfalls to the Mississippi River at approximate RM 859.0: 1) Lime thickening station emergency bypass, 2) screening station discharge, and 3) treatment building discharge. Generally industrial outfalls impact river mixing as previously described. These discharges need more site specific data to make any conclusions regarding the impact of the outfalls on mixing within the river. Monitoring conducted under various flow regimes near the outfalls would allow the delineation of the mixing plume. The exact locations and orientation of the discharge pipes/channels would also need to be known to make specific conclusions about these outfalls. See Appendix D.

River channel morphology

Through this reach the channel is a straight free-flowing river without impoundment or navigation channel. The shallow and wide characteristics of the river within this reach may enhance vertical mixing to the point that a depth-average assumption may be valid. Monitoring data would need to be collected at varying depths to verify this assumption and quantify the extent of mixing.

River islands

Three islands are located at approximate river miles 858.0, 858.1 (on the west bank) and 858.6 (on the east bank). More information regarding the flows around the islands is necessary to draw definitive conclusions regarding the impact of the islands on mixing within the river. Specific mixing data could be obtained by conducting a tracer study.

Dead zones

Dead zones in this reach probably occur in the channels between the islands and riverbanks. Generally dead zones impact river mixing as previously described. Site specific mixing data is required to quantify the effects that these zones have on hydraulic mixing within the river. This mixing data could be gathered through a tracer study.

Water appropriations

Minneapolis and St. Paul municipal water intake is located at RM 862.8 (MDH 2001), approximately four miles upstream of the northern boundary of the MWMO upstream border. According to MDH (2001), the annual appropriations amount to 1.67% of river flow, probably not enough to impact water quality due to the withdrawals. The impact of this withdrawal on using data from gages upstream of the municipal water intake to estimate flow within the MWMO should be further investigated before using monitoring data from above this point.

Bridges

One bridge is located at RM 857.8 (Camden River Bridge). See Appendix E.

Reach #2 (RM 857.8 – RM 854.1): Upper St. Anthony Falls Pool

Elevation

This reach is the first navigational pool on the Mississippi River, held at a higher elevation by Upper St. Anthony Falls dam. Therefore, the surrounding riverbanks are only 30 to 35 feet above the elevation of the river; however, a small upland (70 to 100 feet above the river) occurs in the watershed area to the west of this reach.

Industrial outfalls

The XCEL energy power generation plant has a total of six NPDES permits for discharge to the Mississippi River at approximately RM 856.6. Generally industrial outfalls impact river mixing as previously described. Flows and concentrations of these discharges, as well as outlet configurations, are necessary to make any conclusions regarding the impact of the outfalls on mixing within the river. See Appendix D.

River channel morphology

Reservoir conditions in this stretch of the river are created by Upper St. Anthony Falls Dam. The normal operating elevation of the pool is 799.2 feet. Generally reservoir conditions impact river mixing as previously described. A tracer study on this portion of the river would allow more specific information regarding the effects of river channel morphology on mixing.

River islands

A total of three islands are located in this reach. Two islands are located in one group near the east bank at RM 856.9. The third is Nicollet Island, a large island that stretches from RM 854.6 to 854.1 near the Upper St. Anthony Falls Dam. The east channel around Nicollet Island probably acts as a type of dead zone trapping pollutants for later discharge. More information regarding the flows around the islands is necessary to draw conclusions regarding the impact of the islands on mixing within the river. A tracer study conducted on this reach of the river would provide information on the exact influence of the islands.

Dead zones

Dead zones in this reach probably occur in the east channel around Nicollet Island and behind the dam. Generally dead zones impact river mixing as previously described. Site specific mixing data is required to quantify the effects that these zones have on hydraulic mixing within the river. This mixing data could be gathered through a tracer study.

Lock-and-dam

The Upper St. Anthony Falls Lock-and-Dam is located at RM 854.1. Generally lock and dams impact river mixing as previously described. Site specific mixing data is required to quantify the effects that the lock and dam has on hydraulic mixing within the river. Monitoring downstream of the locks and dams should take into consideration the times when the locks are emptied and filled to properly interoperate monitoring information and flow contributions.

Bridges

Eight bridges cross the Mississippi River at the following locations: RM 857.6 (RR bridge), RM 856.4 (Lowry Avenue), RM 855.8 (RR bridge), RM 855.4 (Broadway Avenue), RM 855.0 (Plymouth Avenue), RM 854.5 (RR bridge), RM 854.3 (Hennepin Avenue), and RM 854.1 (Third Avenue). See Appendix E.

Vessel traffic

This reach contains a nine-foot navigation channel from Upper St. Anthony Falls Dam to RM 857.5. A dredged turning basin is found at RM 857.5. Barges are present in 2003 aerial photos on the west bank north of Lowry Ave. N at RM 856.8 to RM 857.4. Barge traffic impacts river mixing as described above. Throughout this reach, it is probably realistic to assume that three passes of loaded river barges will completely vertically mix the river as found by Stephan 1982 in a similar reach downstream of the MWMO. A mixing study would need to be undertaken to confirm this assumption.

Reach #3 (RM 854.1 – RM 853.4): Lower St. Anthony Falls Pool

Elevation

With a 40-foot drop at the Upper Falls, the Twin Cities Gorge becomes visible in this reach as 70-foot bedrock cliffs. This steep change in elevation from the surrounding land enhances the gradient for efficient stormwater drainage.

Tributaries

Bassett Creek watershed drains approximately 103.6 km^2 (40 mi^2) and enters the Mississippi River at RM 853.7. The lower portion of Bassett Creek was re-routed through a large flood control tunnel to this location in 1997. The outflow of Bassett Creek will have the effect of displacing Mississippi River flow toward the east bank. Additional information such as flow contribution of Bassett Creek and configuration of the outlet is needed regarding the inflow of Bassett Creek to draw further mixing conclusions.

River channel morphology

Reservoir conditions in this stretch of the river are created by Lower St. Anthony Falls dam. The normal operating elevation is 750.0 feet. The river channel dredging in this reach is mostly on the lock (west) side of the river.

River islands

Hennepin Island at RM 853.8 forms a barrier between portions of the river. More information regarding the flows around the island is necessary to draw conclusions regarding the impact of the island on mixing within the river. A tracer study conducted on this reach of the river would provide information on the exact influence of the island.

Dead zones

Dead zones probably occur in this reach within the locks, behind the lower dam, and in the backwater area at Hennepin Island Park. Site specific mixing data is required to quantify the effects that these zones have on hydraulic mixing within the river. This mixing data could be gathered through a tracer study or other study recommended in Section IV.

Lock-and-dam

The lock-and-dams on each end of this reach will cause erosive turbulence at the upstream end of the reach and deposition at the downstream end of the reach. The significant portion of water channeled through the lock areas will have an influence on the mixing within this reach. Site specific mixing data is required to quantify the effects that each lock-and-dam has on hydraulic mixing within the river. Monitoring downstream of the lock-and-dams should take into consideration the times when the locks are emptied and filled to properly interpret monitoring information and flow contributions.

Bridges

One bridge located at RM 853.6 (Stone Arch Bridge). See Appendix E.

Vessel traffic

This reach contains a nine-foot navigation channel. Barge traffic will generally be confined to this channel within this reach as they travel between the upper and lower locks. Vessel traffic impacts river mixing as described above. In this shorter turbulent reach, it is likely that the mixing contributed by barges has a large impact on the west side of the river and a lesser impact near the east shore where the flow is more turbulent. A mixing study would need to be undertaken to confirm this assumption.

Reach #4 (RM 853.4 – RM 847.8): Lock and Dam #1 Pool

Elevation

This reach is set deeply within the Twin Cities Gorge, with 100-foot bedrock cliffs on each bank, providing an efficient gradient for stormwater drainage.

Industrial outfalls

Reach #4 contains 4 NPDES discharge permits. Hiawatha MetalCraft Inc. has an NPDES permit at river mile 850.4 for non-contact cooling water. The Riverview Theater has an NPDES permit at RM 849.0 for non-contact cooling water. A former Phillips 66 Station has a permit for total facility discharge at RM 848.0. Highland Theater has a non-contact cooling water NPDES permit at RM 847.9. Generally industrial outfalls impact river mixing as previously described. This discharge needs more site specific data to make any conclusions regarding the impact of the outfalls on mixing within the river. Monitoring conducted under various flow regimes near the outfalls would allow the delineation of the mixing plume. The exact locations and orientation of the discharge pipes/channels would also need to be known to make specific conclusions about these outfalls. See Appendix D.

River channel morphology

Reservoir conditions in this stretch of the river are created by Lock and Dam #1. The normal operating elevation is 725.1 feet with bladder inflated or 723.1 feet with bladder deflated. The inflatable bladder is part of the dam powerhouse system. This stretch of river also contains the 9-foot navigational channel throughout its reach.

Dead zones

A dead zone may exist on the upriver side of the dam and within the locks. The rest of this reach probably contains very few significant dead zones although further study could identify any others. A tracer study and modeling could identify the extent of the dead zones within this reach.

Lock-and-dam

Lock and Dam No.1 is located at RM 847.6. The lock is on the west river bank. In addition to maintaining a 9-foot navigational channel, this site is used for power generation. Ford Motor Company owns and operates the powerhouse at the east end of the dam. Two inflatable rubber bladders comprise the flashboard system for the powerhouse. Erosive turbulence probably occurs at the upstream end of the reach and deposition in downstream sections of Pool #1.

Bridges

Nine bridges cross the Mississippi River at the following locations: RM 853.2 (I-35W), RM 853.1 (Tenth Avenue), RM 853.0 (RR bridge), RM 852.6 (Washington Avenue), RM 851.7 (I-94), RM 851.5 (Franklin Avenue), RM 850.7 (RR bridge), RM 849.9 (Lake Street), and RM 847.8 (Ford Parkway). See *Section V.D. Emerging Issues*, regarding the I-35W Bridge collapse. See Appendix E.

Vessel traffic

This reach contains a nine-foot navigation channel, with river mixing due to barge traffic as described above. Throughout this reach, it is probably realistic to assume that three passes of loaded river barges will completely vertically mix the river as found by Stephan 1982 in a similar reach downstream of the MWMO. A mixing study would need to be undertaken to confirm this assumption.

Table 3. Comparison of selected big river characteristics that affect mixing within the four reaches of the MWMO.

	Reach #1	Reach #2	Reach #3	Reach #4
Top of Reach	RM 859.0	RM 857.8	RM 854.1	RM 853.4
Bottom of Reach	RM 857.8	RM 854.1	RM 853.4	RM 847.8
Length (mi)	1.2	3.7	0.7	5.6
Bank elevation above river	40 – 45 feet	30 – 35 feet	70 feet	100 feet
Tributaries	Shingle Cr. @ DS end	Shingle Cr. @ US end	Bassett Cr. @ RM 853.7	N/A
Industrial outfalls (NPDES) (see Appendix D for loactions)	RM 859.0 (x3)	RM 856.6 (x6)	N/A	RM 850.4 (x1) RM 849.0 (x1) RM 848.0 (x1) RM 847.9 (x1)
Water appropriations	US @ RM 862.8 (1.67% of annual flow)	N/A	N/A	N/A
River channel morphology (see Appendix C)	Shallow and wide Gentle meander	USAF reservoir Wide→narrow Meanders @ DS	LSAF reservoir Narrow	L&D#1 reservoir Narrow→wide Meanders @ US
River islands	Three (unnamed @ 858.0, 858.1, 858.6)	Three (two unnamed @ 865.9, Nicollet @ 854.6-854.1)	One (Hennepin @ 853.8)	
Bridges (see Appendix E)	One (@ 857.8)	Eight (@ 857.6, 856.4, 855.8, 855.4, 855.0, 854.5, 854.3, 854.1)	One (@ 853.6)	Nine (@ 853.2, 853.1, 853.0, 852.6, 851.7, 851.5, 850.7, 849.9, 847.8)
Dead zones	Bank-side of islands	Bank-side of islands Behind USAF dam	Bank-side of island Behind LSAF dam	Behind L&D#1 dam
Vessel traffic	N/A	Navig. channel DS of 857.5	Channel and lock on west bank	Lock on west bank
Locks-and-dams	N/A	Deposition above USAF	Erosion below USAF Deposition above LSAF	Erosion below LSAF Deposition above L&D#1

RM = river mile
NPDES = National Pollution Discharge Elimination System
DS = downstream
USAF = Upper St. Anthony Falls
US = upstream
LSAF = Lower St. Anthony Falls
L&D#1 = Lock-and-Dam #1

III. Monitoring Protocols

Natural resource monitoring is the collection and analysis of repeated observations or measurements to evaluate changes in condition and progress toward meeting a management objective. Monitoring protocols are detailed study plans that explain how data are to be collected, managed, analyzed, and reported, and are a key component of quality assurance for natural resource monitoring programs. Protocols are necessary to ensure that changes detected by monitoring actually are occurring in nature and not simply a result of measurements taken by different people or in slightly different ways (Oakley et al. 2003). This document is designed to enable the MWMO to evaluate its current monitoring program and guide development of new monitoring protocols; this section reviews the key components of monitoring protocol development, the monitoring protocols for big rivers, and existing monitoring agencies with monitoring stations within the MWMO.

A. Components of Monitoring Protocol Development

Monitoring projects that incorporate a large up-front investment in defining objectives, optimizing sampling designs, and determining how monitoring results will be used are more likely to succeed over the long term. Careful documentation of the questions being asked; the sampling framework and survey design; step-by-step procedures for collecting, managing, and analyzing the data; and expectations on how the data will be presented and used are all part of "getting it right the first time." Key steps in the development of a comprehensive monitoring protocol include aspects of sample design, monitoring procedures, and data management, analysis, and reporting. Quality assurance and quality control measures are part of all of these protocol development steps.

Quality Assurance and Quality Control

Quality assurance is the planned and systematic pattern of all actions necessary to provide adequate confidence, or assurance, that a project outcome optimally fulfills expectations. Quality control is the systematic evaluation of the various aspects of a project to ensure, or control, that the standards of quality are being met. Quality control involves specific tasks undertaken to determine the reliability of field and laboratory data. Together, quality assurance/quality control (QA/QC) is a significant part of any monitoring program. The objective of QA/QC is to ensure that the data generated by a project are meaningful, representative, complete, precise, accurate, comparable, and scientifically-defensible. It is a broad management concept for maintaining the ability to provide reliable information, requiring the complete integration of field and laboratory systems of sample collection and analysis. Therefore, QA/QC incorporates peripheral but essential operations such as survey design, equipment preparation, maintenance tasks, data handling, and personnel training; it is summarized throughout every aspect of a monitoring protocol.

Modular Organization of Protocol

No matter how much advanced planning goes into protocol development, some changes and improvements in such things as field methodology and approaches to data analysis and reporting are to be expected. To accommodate and plan for periodic review and revision, Oakley et al. (2003) propose a modular protocol organization consisting of a protocol narrative, a series of Standard Operating Procedures (SOPs), and a supplementary section of supporting materials. In this way, changes to specific protocol components are more easily documented and tracked through time. A modular organization also facilitates export and adaptation of protocols across ecological regions or agencies. Peer review of protocols and revisions are essential for their credibility. The supplementary documentation should include reviewers' comments and authors' responses.

Standard Operating Procedures

Consistent field and laboratory methods throughout the duration of a monitoring program help ensure that variations in the data represent natural variations of the resource, and not variations due to slightly different methods employed by different field personnel. Oakley et al. (2003) recommend a modular protocol organization including a series of Standard Operating Procedures (SOPs) for key steps in the monitoring process, such as:

- Preparations and equipment setup prior to the field season
- Training observers and staff qualifications
- Using the global positioning system
- Establishing sampling sites
- Measuring and calculating stream flow discharge
- Documenting habitat variables
- Sample collection and field procedures
- Sample processing and contract laboratory requirements
- Data management
- Data analysis
- Reporting and community education
- Procedures and equipment storage after the field season
- Revisions to the protocol

Each of these SOPs is considered a stand-alone document, which works in conjunction with all other SOP components to comprise the required procedures of a protocol.

Sample Design

Sample design is the process of designing a method to collect a scientifically-valid statistical sample of a population. In the case of the Mississippi River, sampling entails collecting sufficient water quality data to fully and accurately describe the conditions of the river reach under consideration. This initial step in protocol development involves assessing current conditions by collecting historical information, devising a set of monitoring questions and objectives, choosing a site selection method, and determining the monitoring and return frequencies necessary to collect valid data.

Historical Background and Assessment – What has been done, and what is known

Developing a monitoring protocol that will last for the long term requires significant up-front investment in thorough investigation of the environmental degradation and risks posed by the resource of interest. This provides the rationale for why a particular resource or resource variable was selected for monitoring, gives background information concerning the resource or resource variable of interest, and discusses the linkages between this and other monitoring projects. Fortunately, the MWMO area is centered on a large river located in a large metropolitan area; several decades of water quality data are available from federal, state, and regional monitoring agencies that maintain current monitoring programs.

Monitoring Questions and Measurable Objectives

After developing an understanding of the environmental problems experienced by a natural resource, protocol developers need to clearly define key monitoring questions that identify measurable objectives for the protocol. When it comes to phrasing monitoring questions, the more generalized questions are less useful. There is a big difference in potential monitoring outcomes (and hence usefulness) of a generalized monitoring question ("How's our water quality?") and a precise monitoring question ("What is the mean monthly fecal coliform bacteria concentrations at the mouths of the tributaries to our river, and how do they compare to water quality standards for recreation and swimming?"). A well-crafted monitoring question will contain elements of the sample design within itself: monitoring parameter, site selection method, sampling frequency, and even data analysis methods can be specified within monitoring questions.

Often, these questions can be developed through scoping workshops with local and regional stakeholder groups, and may cover a range of issues, from hot topics to chronic problems. The MWMO may want to hold stakeholder meetings to determine the important monitoring issues, and turn those issues into monitoring questions. Measurable objectives must be derived from these questions, to enable assessment of the adequacy of the monitoring protocol. Table 4 gives an example of the monitoring questions and measurable objectives of a newly-developed monitoring protocol (Magdalene et al. 2007). The MWMO must go through the careful process of determining its monitoring interests, then defining questions and objectives that serve those interests. This step lays the ground work for identifying subsequent parameters of the sample design process: whether the site selection should be targeted or random, how many sites are needed for efficient yet sufficient monitoring, and how many samples from a site are needed to characterize the site?

Table 4. Monitoring questions and measurable objectives for a newly-developed monitoring protocol (Magdalene et al. 2007).

Monitoring questions for the main stems of the Mississippi, St. Croix, and Namekagon Rivers within two national park units:

1. What are the current status and long-term trend in systematic flow regime?
2. What are the current status and long-term spatial and temporal trends in select water quality variables, including temperature, pH, specific conductance, dissolved oxygen, water clarity, sediment, alkalinity, major ions, and nutrients?
3. Are changes in water quality parameters correlated with tributary influences or changes in other aspects of the ecosystem, such as measures of biotic communities, exotic species, land use or land cover, weather and climate, or atmospheric deposition?

Measurable objectives (in order of priority)

1. Determine historical or reference conditions and interannual range of natural variability for three water quality variables (pH, dissolved oxygen, total phosphorus) using over 25-years historical data from six monitoring sites each on the St. Croix and Mississippi Rivers.
2. Monitor flow in the St. Croix and Namekagon Rivers and gather flow data for the Mississippi River, to determine changes in mean monthly and mean annual flow.
3. Monitor mean annual concentrations of core and advanced suite parameters in MISS and SACN and from the mouths of selected tributaries, accounting for seasonality in water quality conditions.
4. Relate current water quality conditions to known historical conditions using seasonal Kendall trend analysis.
5. Analyze water quality parameters for trends, and correlate any observed trends with potential causes (such as weather, climate, land use, point sources, exotic species, and atmospheric deposition) using multiple regression analysis.

Site Selection Process – Random or Targeted

A monitoring protocol developer must choose a method for selecting the number and location of monitoring sites. Magdalene et al. (2007) contrast the two dominant approaches to site selection that are employed by national monitoring agencies: the targeted-sampling approach of the U.S. Geological Survey (USGS), and the random-sampling approach of the U.S. Environmental Protection Agency (USEPA) Environmental Monitoring and Assessment Program (EMAP). The USGS approach is useful for targeting particular water quality issues or pollution sources, and sites are often selected to monitor subwatersheds based on different surficial geologies and land use patterns. The EPA-EMAP approach is useful for efficient analysis of the overall condition of a natural resource, especially those dominated by dispersed non-point sources of pollution, employing random site selection for statistical sampling of that resource population. The redesign of the MWMO's Monitoring Program could use either or both of these approaches, as long as the targeted sites are not lumped with other targeted sites or the random sites for the calculation of population statistics. Population-wide averages are only valid when calculated from randomly-selected sites.

Number and Location of Sites

The spatial distribution of monitoring sites depends largely on the monitoring goals. Longitudinal spacing of sites is useful for evaluating the evolution of the river water quality as it moves through the system; site identification is usually tied to river mileage. Lateral spacing of sites are critical for evaluating the degree of mixing achieved by the river at any given cross-section; site identification can be river mile plus a letter designation based on cross-sectional position, using A at the west bank and Z at the east bank (i.e., Soballe and Fischer 2004). Vertical samples, or separate samples in a single vertical, are designated based on their collection depth below the water surface at the time of sampling.

Monitoring Frequency and Return Periods Necessary for a Valid Data Set

The selection of monitoring frequency and return periods depend upon 1) the monitoring objectives, 2) the historical variability of water quality data, and 3) the limitations of the monitoring budget. For example, in Table 4, measurable objectives included mean annual concentrations of water quality parameters, taking into account seasonal variability. Through statistical power analysis of the historical data, it was determined that the high intra-annual variability of key water quality parameters required a minimum of semi-monthly sampling to achieve statistically-significant results. However, the monitoring budget would only allow for monthly sampling, so the monitoring protocol compromised with an expectation of lower statistical power for the water quality measures that were most variable. In addition, the limited monitoring budget precluded collecting enough data to calculate annual loading within the rivers. In this way, the details of the monitoring questions and measurable objectives are modified during an iterative process, as the protocol developer determines the amount of monitoring that is feasible. One key step in defining the monitoring questions is documenting the history of decision-making that accompanied protocol development.

As intra-annual variability in flow and water quality parameters increase, the monitoring frequency needed to achieve statistical accuracy increases (Johnson and Stephan 1978). More dynamic flow rates indicate the need for more frequent monitoring, especially if monitoring goals are not just the characterization of ranges and trends in concentrations, but also loading. To support the TMDL process, the MWMO should consider increasing its ability to calculate annual loads at monitoring stations in which it has an interest. Calculating annual loads from a monitoring site requires both background sampling (i.e., monthly) and composite event sampling during several storm events per year, for a total of 20-30 samples per year (e.g., MCES 2003). Making the step up from background sampling to event sampling can entail an order of magnitude (from 2- to 10-times) greater monitoring effort for a monitoring agency. It is a non-trivial, albeit very important, undertaking.

The measurable objectives in Table 4 include an assessment of trends in concentrations (although not trends in loads). An assessment of trends requires a minimum of three return samplings; a trend from two points is not considered valid. The return period (or interval in years between return samplings; i.e., every year, every three years, every ten years) is determined during statistical power analysis; the more return periods in the database, the higher statistical power of the trend results. Typically, statistical power is stated in terms of detection level and return period (i.e., monitoring protocol has 90% power to detect a 20% change in 10 years with bi-annual sampling). The monitoring return period also depends on the interannual variability of the resource.

Monitoring Parameters and Techniques

The monitoring parameters under investigation (i.e., total phosphorus) are specified during phrasing of the monitoring questions and objectives. For starters, the MWMO may want to focus on water quality parameters that have triggered an impaired status listing for a water body upstream, within, or downstream of the MWMO area (see Table 2). In addition, the selection of monitoring parameters should take into consideration potential pollutant sources that are a concern in the contributing areas, for example: nonpoint nutrients, atmospheric pollutants like mercury, pesticides, or PCBs, and persistent trace elements from urban point sources.

The method selected to measure each monitoring variable must be scientifically-defensible. It is common practice to select a nationally-designed monitoring protocol as a starting point; this ensures that the protocol is scientifically-defensible and maximizes the comparability of monitoring results across the nation's watersheds. However, any nationally-designed monitoring protocol should be evaluated for applicability to a local watershed; it may need to be adjusted to the local climate and landscape (e.g., changing sampling frequency). A good monitoring protocol will include extensive testing or evaluation of the local effectiveness of the procedures before they are accepted for long-term monitoring. Often, this is done in the first few years of development of a long-term monitoring program, and through comparison with the protocols used by other local monitoring agencies.

Documenting the Monitoring Process

Keeping careful documentation of the steps in the monitoring process helps to ensure that the protocol was followed. In addition, should problems with the quality of the monitoring data arise, thorough documentation could help reveal the source of the problem and enable possible recovery of the data. Documentation topics include the following: calibration and maintenance of monitoring equipment, recording field observations and problems encountered during fieldwork that may have a bearing on the quality of the data, maintaining chain-of-custody when samples are sent to a contract analytical laboratory, and verifying the quality of data that is returned from in-house and contract laboratories.

Data Management, Analysis and Reporting

Establishing standard methods for the management, analysis, and reporting of monitoring data is a critical step in the usability of the data. The data must be maintained in a database that is accessible to resource managers and the public, routinely analyzed to determine the meaning behind the data, turning it into useful information, and the information disseminated to policy-makers and the watershed community.

Data Management

Any monitoring protocol should have explicit plans for how it is going to manage the data and metadata generated by its monitoring activities. Monitoring data values, and the associated metadata (monitoring date, location, personnel, method, etc.) necessary to interpret the data, should be recorded in an electronic database. This helps preserve the data from loss and makes it accessible to others for analysis of complex data sets. A monitoring agency that is developing or re-designing a monitoring protocol should plan to create a custom-designed database for their data (i.e., an MS-ACCESS relational database) and/or plan to upload their data into an established database (i.e. EPA's STORET). In the best case scenario, the monitoring database is made accessible to interested resource managers via on-line internet access. The MPCA is a good example of how a monitoring agency can provide a user-friendly interface to allow resource managers and the public to look at maps of monitoring locations and to click links to the associated water quality monitoring record (http://www.pca.state.mn.us/data/edaWater/).

Data Analysis

Data analysis is the process of turning scientific data into useful information. All monitoring protocols should include provisions (time and staffing) for routine analysis of data collected for the protocol. This analysis could be as simple as summary statistics (number, mean, and range of sampling values) for an individual site or for a population (groups of randomly-selected sites lumped together). Side-by-side box-plots are an example of graphical representations for comparing this kind of data. Analysis of spatial variability across a resource can be conducted by a two-sample comparison of summary statistics from different sites, to verify that the difference between sites is statistically significant. Analysis of temporal variability at each site or within a population is commonly analyzed using a seasonal Kendall trend test.

One important step in the data analysis process is to check the validity of the a priori power analysis or assessment of the historical data. Statistical power analysis should be conducted on the data collected under the new protocol, once the database has sufficient number of sample data. If environmental conditions or land use patterns have changed since historical times, the protocol under current condition may not have sufficient statistical power to achieve the monitoring objectives. The sample design may need to be modified from the original design (i.e., adjusting sampling frequency or return period, or if necessary, adjusting monitoring objectives to lower the expected power).

Data Reporting

Once the monitoring data has been transformed into information, it must be disseminated to interested parties that will use the information, such as for community education or policy decision-making. The monitoring protocol should describe the expected reporting frequency (i.e., annual monitoring reports, trend report every five years), how the information will be published and distributed, and how monitoring results will inform management decisions.

B. Big River Monitoring Protocols that Support MWMO Goals

One objective of this report is to recommend monitoring protocols that support the goals of the MWMO's monitoring program (www.mwmo.org/Monitoring.html), which are:

- Monitor water quality within the watershed:
    - baseline data to characterize water quality and identify pollutants that exceed water quality standards
    - pollutants listed on the Minnesota "[Impaired] Waters" list for the TMDL process
- Develop and agree upon a standardized set of parameters, sample collection, data analysis, and reporting standards for monitoring in the watershed
- Develop partnerships with other organizations and/or agencies inside and outside the watershed boundaries to improve water quality in the Mississippi River
- Develop [an understanding of] land use impacts on water quality
- Following watershed resources assessment and inventory, monitor biological, chemical, and physical parameters

Although the goals of the monitoring program are general in nature, they provide direction from which to further define specific monitoring objectives and questions. The MWMO recognizes the need to bring together disparate aspects of its monitoring design into a comprehensive monitoring protocol. This current study is a step in the ongoing process of developing a comprehensive monitoring program for a big river system.

The monitoring protocols that could support these goals are grouped below (Table 5 presents a summary of these protocols).

Assessment of Mixing

The process of monitoring site reconnaissance should include an assessment of whether a big river sampling location is reasonably well-mixed. To maximize work efficiency and the monitoring budget, multiparameter sondes can be used to evaluate a suite of field measurements to determine whether a particular site is mixed or unmixed. The criteria to determine whether a site is well-mixed range from simple to rigorous:

1. The EPA-EMAP for big river monitoring (Angradi 2006) assumes that any flows less than 1 meter deep are sufficiently well-mixed, and that any flows greater than 1 meter deep are not.
2. The USGS Long-Term Resource Monitoring Program (LTRMP) assumes that shallow and fast flows are reasonably well-mixed (Soballe and Fischer 2004). However, when water depth exceeds 1.9 meters and flow velocity is less than 0.1 m/s, then an LTRMP monitoring location is considered mixed if differences between the top and bottom of the water column meet all of the following criteria: temperatures differ < 2.0 ºC, oxygen differs < 4.0 mg/L, and specific conductance differs < 50-percent.
3. The National Field Manual (USGS TWRI Book 9, var. dated) recommends a series of transverse and depth measurements (of T, pH, DO, SC) using multiparameter sondes: if these vary by less than 5-percent, then the location is considered reasonably well-mixed.

If the site is mixed, a single sample can be considered to be representative of the site and the site can be monitored by a single sample collected from the river at the centroid of flow. The centroid of flow, which is determined from a series of transverse and depth measurements of flow, is the location in a river's cross-section that 50% of the flow is to the right and 50% of the flow is to the left. An attempt should be made to determine whether the centroid of flow is fixed for the observable range of discharge (i.e., is located in the same position for low, medium, and high flows).

Monitoring from Unmixed Locations

The National Field Manual (NFM) (USGS TWRI Book 9, var. dated) recommends avoiding sampling from unmixed locations. If it is unavoidable, then subsamples must be collected isokinetically: depth-integrated and flow-weighted so that each unit of discharge at that location is equally represented in the averaged sample. The subsamples are collected at several verticals in the river cross-section using a depth-integrating isokinetic sampler either 1) at constant sampling rate in unequal volumes using equal width increments (EWI) between the verticals or 2) at variable sampling rates in equal volumes using equal discharge increments (EDI) between the verticals (see NFM 4.1.3.A). Subsequently, subsamples can 1) be analyzed separately in the laboratory and mathematically averaged for each vertical and within the cross-section, or 2) be composited in the field, mixed thoroughly, and split into aliquots, using a churn splitter or a cone splitter, effectively averaging the water quality at that location. The number of subsamples collected at each vertical can vary:

1. Soballe and Fischer (2004) summarize the criteria used by the USGS-LTRMP for additional depth samples of river sites. When water depth exceeds 1.9 meters and flow velocity is less than 0.1 m/s, two separate samples from the top and bottom of the water column may be collected if differences between the top and bottom of the water column meet any of the following criteria: temperatures differ > 1.9 C, oxygen differs > 3.9 mg/L, or specific conductance differs > 50 percent.
2. The EPA-EMAP big river monitoring (Angradi 2006) criteria for the collection of composited depth samples is based solely on total depth of flow: 1) for flows 1-2 m deep, two samples from the top and bottom of the water column are collected and 2) for flows > 2 m deep, three samples from top, middle, and bottom of the water column are collected.

Physical Monitoring Parameters – Underlying Structure

Flow gaging

Flow gaging is a challenging measurement requiring an understanding of the relationship between water level or stage and channel geometry at a given location. The recognized authority on flow measurement protocols is the U.S. Geological Survey, which operates a network of flow gages on the nation's streams and rivers. Applications of Hydraulics: Surface water techniques. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3 (USGS, variously dated) contains protocols for all aspects of collecting flow data: e.g., measuring stage, measuring and calculating discharge, calculating stage-discharge rating relationships, establishing and maintaining permanent flow gages. The MWMO should consult these protocols for flow gaging of stormwater outfalls in order to collect the annual discharge data necessary to calculate pollutant masses and mean annual concentrations being mixed into the Mississippi River.

Substrate sampling

There are two national protocols for collecting river substrate for toxicology of persistent contaminants, and one for sediment budgets. The USGS method (Shelton and Capel 1994) of collecting bed sediments targets low-flow depositional zones that yield fine-grained particles conducive to sorption of trace elements and hydrophobic organic chemicals. This is usually conducted in conjunction with sampling of fish tissue for the same pollutants within the same reach. The MCES method (EPA 2000) collects three transverse bed sediment samples for toxics (metals, pesticides, hydrocarbons), along with macroinvertebrates and sediment pore water quality. The USACE method (USACE 1995) of collecting bed sediments focuses on bulk sampling to describe particle-size distributions and identifying bed-load sediment movement within the river channel.

Chemical Monitoring Parameters – Water Quality

Field parameters

Field parameters are those measures of water quality that are so sensitive to local conditions that they must be recorded in-situ (in place): temperature, pH, Eh, specific conductivity, and dissolved oxygen. Turbidity is sometimes included in this list of parameters, but reliable turbidity probes have yet to be developed. The USGS developed national standards for the measurement of field parameters as early as the 1950s, and continues to be the authority on measurement of field parameters. The monitoring protocols of state and local organizations typically defer to the National Field Manual for the Collection of Water-Quality Data: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 9 (USGS, variously dated). Modern methods include multiparameter sondes with a collection of probes for measuring field parameters with depth. Where samples are collected at more than one depth, the median value of field parameters should be recorded for a discharge-weighted (EDI) or areal-weighted (EWI) value at that location (see NFM 6.0.2.B).

Suspended solids and sediments

Several federal agencies have collaborated to standardize sediment sampling equipment and techniques, via the Federal Interagency Sedimentation Project. The USGS (Edwards and Glysson 1999) draws a distinction between the common measurement of total suspended solids (TSS), which can include colloidal and organic particulates, and the less commonly measured suspended sediment concentration (SSC). TSS is more closely tied to measures of turbidity and clarity; regulatory agencies like the MPCA generally rely on TSS as a measure of suspended particulates due to its ecological implications. The MCES adds a measure of the organic solids by pairing analyses of TSS with VSS (volatile organic solids) (MCES 2003). In contrast, SSC is measured by the USACE (1995) as part of a sediment transport mass balance.

Inorganic chemistry, including nutrients

The National Field Manual (USGS, var. dated) contains the sample collection methods for inorganic compounds, including nutrients (see NFM 5.2.1 and 5.6.2). The USEPA approves a list of sample handling and laboratory analytical methods that are required for the analysis of the chemical and biological components of wastewater, drinking water, sediment, and other environmental samples that are outlined by the Safe Drinking Water Act (SDWA) and the Clean Water Act (CWA) (see: http://www.epa.gov/waterscience/methods/ method/index.html). Contract laboratories hired to analyze SDWA or CWA (including TMDL) waters are required to document the use of these methods. The "Standard Methods for the Examination of Water and Wastewater" is a joint publication of the American Public Health Association (APHA), the American Water Works Association (AWWA), and the Water Environment Federation (WEF), currently in its twenty-first printing (see http://www.standardmethods.org/). This comprehensive and expensive reference covers all aspects of water and wastewater analysis techniques, but, in practice, has been superceded by free, up-to-the-minute web access. In addition to the above U.S. EPA website, a free on-line searchable clearinghouse of methods is available from the National Environmental Methods Index (http://www.nemi.gov/).

Pesticides

The NFM (USGS, var. dated) contains the protocol for collection of pesticide samples using solid-phase extraction (see NFM 5.3 and 5.6.1). The MDA Agricultural Chemical Monitoring and Assessment Program, as directed by the Minnesota Pesticide Control Law, has designed a monitoring protocol (MDA 2006) for detection of base-neutral and acid pesticide concentrations in the surface waters of Minnesota. The protocol recommends that 4 to 8 baseflow or stormflow samples be collected from mid-May to mid-July, using grab sampling or composited automatic sampling.

Volatile organic compounds

The NFM (USGS, var. dated) contains the sample collection method for organic compounds (see NFM 5.2.2 and 5.6.1). The USEPA publishes the sample handling and laboratory analytical methods that it requires industries and municipalities use to analyze the chemical and biological components of wastewater, drinking water, sediment, and other environmental samples that are outlined by the Clean Water Act and the Safe Drinking Water Act (see: http://www.epa.gov/waterscience/methods/method/index.html).

Biological Monitoring Parameters – Aquatic Health

Algae, Macroinvertebrates, and Fish

The USEPA recently released a new monitoring protocol for bioassessment of large rivers (Flotemersch et al. 2006) for biological water quality parameters that are often considered to be efficient integrators of physical and chemical water quality conditions, including algae, macroinvertebrates, and fish.

Riparian vegetation

The USGS (Johnson and Zelt 2005) has developed a protocol for mapping and categorizing riparian vegetation, which may prove helpful to the MWMO in tracking the riparian health of the river.

Figure 3. Example of recommended field equipment for monitoring large river sites (from Angradi et al. 2006). Apparatus for attaching instrument sensors and sample-collecting hoses to the sounding weight (30 lbs in this picture). A sounding-weight hanger-bar has been fabricated to accommodate a Hydrolab DataSonde. The DataSonde is attached to the hanger bar, facing forward, with stainless hose clamps (covered by tape in this picture). The hose to the peristaltic pump (small diameter) is taped to the DataSonde. The hose to the high volume Guzzler pump (large diameter) is attached to the hanger bar with plastic cable ties. A one-way valve is attached to the end of the Guzzler hose. When the apparatus is lowered, the instrument cables and hoses are attached to the winch line with cable ties.

Monitoring Parameter Category	Lead Agency (Protocol Reference)	Monitoring Objective	Monitoring Parameters
Mixing assessment	EPA (Angradi 2006)	Mean conc., annual load	Flow depth
	USGS (Soballe and Fischer 2004)	Mean conc., annual load	T, pH, SC, DO
	USGS (USGS TWRI Book 9, var. dated)	Mean conc., annual load	T, pH, SC, DO
Monitoring unmixed locations	USGS (USGS TWRI Book 9, var. dated)	Mean conc., annual load	Various, incl. flow
Flow gaging	USGS (USGS TWRI Book 3, var. dated)	Continuous discharge	Stage, discharge
Substrate	USGS (Shelton and Capel 1994)	Toxicology	Toxic conc. in seds
	MCES (EPA 2000)	Toxicology	Toxics, pore water, macroinvertebrates
	USACE (USACE 1995)	Sediment budget	Sediment mass, grainsize distrib.
Field parameters	USGS (USGS TWRI Book 9, var. dated)	Concentr'tn	T, pH, SC, DO
Suspended solids and sediments	USGS (Edwards and Glysson 1999)	Mean conc., annual load	TSS
	MCES (MCES 2003)	Mean conc., annual load	TSS, VSS
	USACE (USACE 1995)	Sediment budget	Sediment mass, grainsize distrib.
Inorganic chemistry and nutrients	USGS (USGS TWRI Book 9, var. dated)	Mean conc., annual load	Ions, nutrients
Pesticides	MDA (MDA 2006)	% Detect	Base-neutral, acid pesticides
Volatile organic compounds	USGS (USGS TWRI Book 9, var. dated)	% Detect	VOC, PAH, PCB, etc.
Biological	USEPA (Flotemersch et al. 2006)	Ecol. Health	Algae, fish, macroinvertebrate
	USGS (Johnson and Zelt 2005)	Ecol. Health	Riparian land cover

Table 5. Summary of monitoring protocols for potential use within the Mississippi River within the MWMO area.

C. Existing Monitoring Programs with Monitoring Stations Within the MWMO

Many different regulatory institutions have a stake in the water quantity and quality of the Mississippi River. For this reason many monitoring programs include the river and its major tributaries. After developing specific monitoring objectives, the MWMO should evaluate whether existing monitoring programs can help the MWMO extend its monitoring budget, by coordinating with their monitoring efforts. The following sources of data are reliable and have quantities of information that may be valuable, for both analyses of historical data (much of it available from Legacy STORET) and future water quality data. Table 6 summarizes the existing monitoring programs within the MWMO, detailing their monitoring objectives, number and location of monitoring sites within the MWMO, sampling frequency, and return period.

U.S. Geological Survey (USGS)

Flow monitoring

The USGS network of gages on the nation's streams and rivers provides valuable flow data for water resource managers. The protocols for such sites conform to the TWRI Book 3 (USGS, var. dated). The gages provide information on flow levels at key locations in the nation's drainage network; some of the data is accessible on-line as real-time data. Not only is the data useful for understanding the quantity of water in streams and rivers, tracking flood or drought levels, but, when linked with water quality measurements, the flow data is essential for calculating pollutant loads and evaluating loading behavior. None of the USGS gages are located within the MWMO area, but several are located nearby, on the Mississippi River (at Anoka, Coon Rapids, and St. Paul, MN) and on a tributary that contributes to the MWMO area (Shingle Creek). These flow gages provide information about river flows upstream and downstream of the MWMO area.

Water quality monitoring

Due to budget cuts in the late 1990s, the USGS stopped routine collection of water quality samples at its flow gaging sites; it now conducts very infrequent water quality monitoring at its flow gaging sites (or none at all).

National Park Service (NPS)

Large Rivers Water Quality Monitoring Program

The Great Lakes Inventory and Monitoring Network is comprised of nine national park units in Minnesota, Wisconsin, Michigan, and Indiana, including the Mississippi National River and Recreation Area (MNRRA). The Large Rivers Water Quality Monitoring Program includes five sites on the Mississippi River: above the mouth of the Crow River, Coon Rapids Dam reservoir, Fridley, upper Pool 1, and Spring Lake. Monitoring at these sites follows the protocol developed by Magdalene et al. (2007). Due to budget constraints, these sites are only monitored for selected parameters on a biennial monthly basis. One of these sites is located immediately upstream of the northern boundary of the MWMO area at RM 863.1, and one site monitors Pool 1 above Lock-and-Dam #1, at RM 852.3.

Minnesota Pollution Control Agency (MPCA)

Milestone River Monitoring Program

In 1994, the MPCA re-organized its river monitoring program, selecting from among previous monitoring sites those sites that had long monitoring histories (some as far back as 1953) and that well-represented a river reach. This long-term monitoring program was designed to gain an understanding of the overall health trends of Minnesota's rivers. Details regarding the protocol for this program can be found at: http://proteus.pca.state.mn.us/water/milestone.html. One of the Milestone sites is located on the Mississippi River at the upstream boundary of the MWMO.

Major Basin Outlet Monitoring Program (proposed)

In spring 2007, the MPCA began developing a new monitoring program to measure loads (not just concentrations) from the outlets of all 81 MDNR major watersheds (USGS 8-digit HUC areas) in Minnesota. The protocol will include flow monitoring and sufficient pollutant sampling to calculate annual loads from each major watershed. In 2007, the MPCA began sampling from 20 of these watersheds, and will eventually expand the program to include all 81 watersheds. The MWMO lies within one of those 81 watersheds (HUC #07010206), a segment of the Mississippi River draining 1016 square miles of the central metropolitan area, from Dayton, MN to Prescott, WI (between the Crow and St. Croix Rivers). It is not known at this time when HUC #07010206 outlet load monitoring will begin.

Total Maximum Daily Load (TMDL) Program

For each pollutant that causes a Minnesota water body to fail to meet state water quality standards, the federal Clean Water Act requires the MPCA to conduct a TMDL study and submit it for approval to the USEPA. TMDL studies set the environmental goals and recommend approaches (implementation plans) for improving water quality. The development of a TMDL represents a significant step-up in monitoring efforts, shifting from a framework of tracking concentrations to a framework of tracking loads, requiring much higher frequency sampling correlated to a continuous flow record. The federal protocols for TMDL development can be found at http://www.epa.gov/owow/ tmdl/techsupp.html, and the state protocols for TMDL development can be found at http://proteus.pca.state.mn.us/water/tmdl/tmdl-publications.html#protocols. Downstream of the MWMO, the Lake Pepin Eutrophication TMDL Implementation Plan will establish wasteload (point source) and load (nonpoint source) allocations for upstream phosphorus sources, including the MWMO area. The MWMO will be expected to cooperate in identifying sources and achieving reductions in loading to the Mississippi River. In addition, TMDLs for various pollutant impairments upstream of the MWMO are being developed, and the MWMO may want to track those projects.

Minnesota Department of Agriculture (MDA)

Agricultural Chemical Monitoring and Assessment Program - Urban Watershed Pesticide Monitoring

As directed by the Minnesota Pesticide Control Law, the MDA is responsible for the detection of base-neutral and acid pesticide concentrations in the surface waters of Minnesota. The protocol (MDA 2006) recommends that 4 to 8 baseflow or stormflow samples be collected from mid-May to mid-August, using grab sampling or composited automatic sampling. One of the program's sites is on Bassett Creek: atrazine (especially during baseflow and early summer storms) and several acid pesticides (especially during storm events) were detected during six sampling dates in 2006.

(See: http://www.mda.state.mn.us/chemicals/pesticides/maace.htm)

Minnesota Department of Natural Resources (MDNR)

Mississippi River Critical Area Program

The MDNR is responsible for administration of the Mississippi River Critical Area Corridor, the boundaries of which coincide with the boundaries of MNRRA. The MDNR collaborates with the NPS on projects within the corridor, but at this time does not conduct any monitoring activities.

Metropolitan Council Environmental Services (MCES)

River Monitoring Program

The MCES River Monitoring Program is comprised of several sub-programs, including River Water Monitoring, Biological Monitoring, and Riverbed Sediment Monitoring. All protocols are described at http://www.metrocouncil.org/environment/RiversLakes/ Rivers/index.htm. These monitoring efforts are conducted at numerous large river sites, including two locations on the Mississippi River at the upper and lower boundaries of the MWMO (RM 862.8 and RM 847.7).

Stream Monitoring Program

The MCES Stream Monitoring Program supports regional planning and modeling efforts, promotes local resource stewardship, and helps establish target pollutant loads for each subwatershed. The protocol is described at http://www.metrocouncil.org/environment/ RiversLakes/Streams/index.htm and within a report by MCES (2003). One of the Watershed Outlet Monitoring Program (WOMP) sites is located 1.9 miles upstream of the Bassett Creek outlet. Although this monitoring site is located outside of the MWMO area, Bassett Creek water quality has significant influence on the Mississippi River within the MWMO area.

Watershed Management Organizations (WMOs): SCWMC & MWMO

Shingle Creek Watershed Management Commission (SCWMC) monitors two sites on Shingle Creek, near its outlet and at mid-watershed. Although these monitoring sites are located outside of the MWMO area, Shingle Creek water quality has significant influence on the Mississippi River within the MWMO area.
(See: http://www.shinglecreek.org/wqlstrsccs.shtml)

Mississippi Watershed Management Organization (MWMO) monitors six sites along its portion of the Mississippi River and five stormwater outfall sites as they discharge to the Mississippi River.

Table 6. Agencies having monitoring programs with existing monitoring sites within or adjacent to the MWMO.

Agency – Program	Parameter Category	Monitoring Objective	Monitoring Sites and Location	*Sampling Freq	**Return Period	Specialized Monitoring Instruments
USGS	Flow	Annual discharge	RM 864, RM 839, and Shingle 1.5	Continuous	1/1	Stage gage Flow meter
NPS – Large Rivers	Field, Sed, Nutr.	Conc. Trends	RM 863.1 and RM 852.3	Monthly	1/2	Sonde, depth-integr. sampler
MPCA - Milestone	Field, Sed, Nutr, Bio	Conc. Trends	RM 859	Monthly	2/5	Field probes
MPCA – Outlets	Field, Sed, Nutr	Annual loads	RM 812	Monthly + storms	2/5	Auto sampler
MDA – Urban WS	Pest, Nutr	% Detection	Bassett Cr.	6x/summer	1/1	
MCES – River water	Field, Sed, Nutr, Bio, Toxics	Conc. Trends	RM 862.8 and RM 847.7	Weekly-Annually	1/1	Field probes, boat
MCES – River Bio	Bio	Conc. Trends	RM 862.8 and RM 848.0	Annual	1/1	
MCES – Bed Seds	Bio, Toxics	Impairments	RM 848.5	Annual	1/10	
MCES – Stream water	Field, Sed, Nutr, Bio, Toxics	Annual loads	Bassett 1.9	Monthly + storms	1/1	Auto sampler
SCWMC – Streams	Field, Sed, Nutr, Bio	Annual loads	Shingle 0.5 and Shingle 5.0	Biweekly + storms	1/1	Auto sampler
MWMO – River	Field, Bio	Baseline and Impairments	RM 859.1, 857.8, 854.9, 852.2, 849.9, and 848.2	Weekly + storms		
MWMO – Stormwater outfalls	Field, Sed, Nutr, Bio, Metals, VOCs	Baseline and Impairments	RM 857.2, 854.8, 853.2, 853.0, and 851.6	Monthly + storms		Auto sampler

* Sampling frequency indicates the number of sampling events per year.

**Return period indicates the number of years sampled (e.g., 2/5 = sampling two out of every five years).

Additional information necessary to support monitoring protocols:

Information about land uses, pollutant sources, and climate variability help water resource managers evaluate and assess water quality results. Available sources include the following:

Land use

- Generalized Land Use for the Twin Cities Metropolitan Area (Metropolitan Council 1990, 1997, 2000, 2005).
- National Resources Inventory (USDA-NRCS 1982, 1987, 1992, 1997, 2001, 2002)
- Land Cover/Use of Pool 1 floodplain riparian areas (USGS-UMESC 1891, 1989)
- 1:250000 & 1:100000 Scale Land Use Land Cover (USGS 1998)
- National Land Cover Dataset (USGS 1992, 2001)

Pollutant sources

- What's in My Neighborhood on-line maps and lists of contaminated sites, for both non-agricultural (http://www.pca.state.mn.us/backyard/neighborhood.html) and agricultural pollutants (http://www.mda.state.mn.us/chemicals/spills/incidentresponse/neighborhood.htm)
- Environmental Data Access features on-line maps and lists of MPCA monitoring and NPDES sites (http://www.pca.state.mn.us/data/edaWater/index.cfm).

Climate Information

- Current and historical temperature and precipitation data, helpful for the interpretation of climate variability (e.g, wet years versus dry years), is available on-line from the Minnesota Climatology Working Group (http://climate.umn.edu/).

D. Other Considerations

Remote accessibility of real-time data

The USGS is a good example of how an agency can not only collect monitoring data, but make it immediately accessible to resource managers or even the public. (See: http://waterdata.usgs.gov/mn/nwis/nwis) It requires investment in reliable monitoring equipment, adequate computer storage for accessing the real-time data, and web-programming to deliver useful information. Real-time data is available immediately and is often at higher temporal resolution than the calculated mean values that go into long-term storage databases. The data that are stored in long-term databases must go through rigorous quality checks to verify its accuracy and note its precision, and therefore, take longer before they can be released to the public.

Safety Considerations

Several safety concerns affect the sample design process. During the site selection process, the areas immediately upstream and downstream of lock-and-dam structures should be declared off-limits as potential sampling sites. When sampling from a large river with actively-used navigational channels, the monitoring design must plan for the use of motorized boats to enable monitoring personnel to get out of the way in case a barge passes in the middle of their sampling procedure. Most of the time, storm sampling is accomplished using automatic samplers; if monitoring personnel need to be in the field at this time, care should be taken to avoid slippery areas or flood conditions.

Emerging Issues in Water Quality Monitoring

Bridge Collapse

The sudden collapse of the I-35W Bridge over the Mississippi River within the MWMO area will: 1) have immediate effect on flow turbulence and mixing patterns within the river, 2) have short-term effect on water quality downstream of the collapse site, 3) result in disrupted flow patterns during the clean-up and construction phases, and 4) eventually stabilize to a new equilibrium of flow and water quality. Possible long-term consequences for river water quality of the bridge collapse include the persistent leaching of hazardous chemicals from deposits in bed sediments and along riverbanks, which may have been deposited during the emergency drawdown at L&D#1.

New monitoring parameters

Emerging contaminants, or those contaminants that have not previously been monitored, primarily enter the environment through municipal wastewater discharge (http://toxics.usgs.gov/regional/emc/index.html). A current list of candidates from the MPCA includes: antibacterial compounds, alkylphenols, black carbon, brominated flame retardants, chiral compounds, coal tar seal coatings, endocrine-disrupting compounds, ethanol plant emissions, fish contaminants, methamphetamine laboratory residues, microbial pathogens, nanotechnology, perchlorate, perfluorochemicals, personal care products, pesticide degradation products, pharmaceuticals, plasticizers, and pyrethroids in sediment. The USGS has developed sampling protocols for some of these compounds (http://water.usgs.gov/owq/FieldManual/chapter5/5.6.1.F_v-1.1_4-03.pdf), and the U.S.E.P.A. has begun developing laboratory methods for detecting some of these compounds (see: http://www.epa.gov/waterscience/methods/method/other.html). When these contaminants are first identified they are often very expensive to monitor until the development of new technologies and economies of scale make it possible to establish a monitoring program. In Minnesota, the MPCA (2004) and MDH (2001) take the lead on identifying emerging contaminants that threaten the designated uses of Minnesota's water resources and on making recommendations to monitoring agencies. No major changes to monitoring protocols are expected until the state establishes water quality standards for any of these compounds. The MWMO may want to track these developments.

New monitoring techniques

A recently developed monitoring technology is flow gaging using an acoustic Doppler velocity meter (ADVM). Morlock et al. (2002) describe ADVMs as small, easy to install and maintain, and they can be used with greater accuracy and efficiency where conventional methods cannot be used. In particular, one application is on the downstream side of a bridge pier, where the ADVM can account for the turbulence zone around the pier. Bridges immediately downstream of a lock-and-dam (e.g, Third Avenue bridge, Stone Arch bridge, or I-35 bridge) are probably not appropriate for this method, due to pervasive turbulence.

Remote sensing of water quality parameters creates the potential for highly-detailed water quality assessments that cover large areas in a short period of time. However, the technique has been most successful for, and may be limited to, water quality parameters that can be correlated to measurements of spectral reflectance (e.g., turbidity, TSS, and chlorophyll-α). At present, there are no remote sensing techniques for dissolved water quality parameters.

Hypoxia in the Gulf of Mexico

The Upper Mississippi River Basin (UMRB) Water Quality Plan (MPCA 2003) lists hypoxia in the Gulf of Mexico as a leading emerging issue for the UMRB (above Hastings, MN), which includes the MWMO area. Currently, issues pertaining to excess nutrients focus on phosphorus-laden sediments as the limiting factor in eutrophication of local lakes, reservoirs, and riverine lakes (e.g., Lake Pepin). However, the greater mobility of nitrogen causes concern much farther downstream, and the far-reaching impacts of nitrogen make it more challenging to coordinate environmental management efforts on such a large spatial scale. The current federal approach to water quality impairments, the TMDL framework, may not be up to the task of remediating pollutant loading in an area the size of the entire Mississippi River basin.

Climate Change in Minnesota

Most climatologists agree that global changes in climate patterns are occurring, and will continue to occur over the next century. It is less clear though, how global climate change will impact the work of water resource managers in Minnesota. Recent significant climate change trends in Minnesota and the western Great Lakes region include 1) warmer winters and higher minimum temperatures, 2) increased frequency of tropical dewpoints, and 3) amplified variability of precipitation and greater contribution from thunderstorms. Possible implications for these trends (personal communication, climatologist Mark Seeley), include the following:

From warmer winters and higher minimum temperatures:

- Change in depth and duration of soil and lake freezing
- Longer outdoor construction season
- Change in over winter survival rates of insect pests and plant diseases, and soil microbes
- Reduced energy use for heating
- Increased number of freeze/thaw cycles
- Change in animal migration, hibernation, and foraging
- Longer exposure times to mold and allergens

From increased frequency of tropical dewpoints:

- Dynamics of pathogen, insect, and microorganism populations
- Efficacy and persistence of herbicides
- Elevated water temperatures, algae blooms
- Increased workload in heat related health care (exposure differentials, MS, COPD, obesity)
- Increased stress on livestock (change in ration, water, reduced milk production and reproduction problems)
- Increased demand for air conditioning

From amplified variability of precipitation and greater contribution from thunderstorms:

- Irrigation, drainage, runoff, sediment, and shoreline management
- Change in storm sewer runoff design
- Amplified hydrographs, lake level variation
- Mitigation of soil erosion
- Mitigation of increased flooding potential
- Mitigation of blowing snow and management of roads and highways

On-going Water Resources Information Forums

Monitoring Agencies

Additional information regarding Mississippi River water quality data and monitoring protocols can be gotten from agencies conducting on-going monitoring. In Minneapolis, the lead water regulatory agencies are the MCES, MPCA, and MDH. The MWMO will want to track developments in water quality rules from these agencies (e.g., expansion of the TMDL program, updates on emerging contaminants, etc.).

- Metropolitan Council Environmental Services (http://www.metrocouncil.org/environment/RiversLakes/)
- Minnesota Department of Health (http://www.health.state.mn.us/)
- Minnesota Pollution Control Agency (http://www.pca.state.mn.us/)
- USGS Upper Midwest Environmental Sciences Center (http://www.umesc.usgs.gov/)

Environmental Organizations

Upper Mississippi River Basin Association (UMRBA), dedicated to coordinating river-related activities, with representatives from state governments, state agencies, and federal agencies (http://www.umrba.org/)

Friends of the Mississippi River (FMR), focusing on watershed protection in the Twin Cities metropolitan area (http://www.fmr.org/)

Upper Mississippi Basin Stakeholders Network (UMBSN), dedicated to sharing information between stakeholders (http://www.umbsn.org/)

Upper Mississippi River Conservation Committee (UMRCC), focusing on preservation and wise utilization of natural resources (http://www.mississippi-river.com/umrcc/)

Great River Greening, focusing on restoring natural areas and open spaces in the Twin Cities area (http://www.greatrivergreening.org/)

Conferences

Minnesota Water Resources Conference (grand merger of four conferences), facilitates interaction among water resources professionals, last meeting October 23-24, 2007 at the Earle Brown Heritage Center in Brooklyn Center, MN (http://wrc.umn.edu/waterconf/)

Mississippi River Research Consortium, 40th annual meeting on April 24-25, 2008 at the Grand River Center in Dubuque, IA. (http://www.umesc.usgs.gov/mrrc.html)

IV. Influence of Hydraulic Setting on Monitoring Protocols

This section provides information on the influence of hydraulic setting on monitoring protocols. Some site-specific information is discussed here and, where information is not available, information gaps are discussed. This section examines the ability to correlate monitoring data between reaches, and monitoring protocols for different hydraulic settings.

A. Comparing Monitoring Data Between Reaches

Comparing monitoring data between the four reaches (and beyond the MWMO) must be done carefully, as it appears that some information can be correlated between reaches and other data cannot. For many parameters there is not enough information to say whether or not data can be correlated among reaches. A monitoring program with solid protocols will provide insight where data gaps exist; further information on data gaps and methods to fill them is located in Section V.

Water Quantity

Stage

Reaches #2, #3, and #4 are characterized by reservoir conditions; each reach terminates in a lock-and-dam structure, forming a reach-long pool held at a single stage level (i.e., elevation above mean sea level). The stage of each reach must be measured separately as each reach is held at a unique elevation by its dam (except free flowing Reach #1). No stage data exists within Reach #1. Upstream of Reach #1, and downstream of the Coon Rapids Dam, is a USGS stage and flow gauge station; this is the closest gauge to the reach but should not be used as a proxy for stage data within the reach until further data collection shows the correlation between this gauge and the stage for Reach #1. Stage data from Upper St. Anthony Falls Dam may be used for Reach #2, stage data for Reach #3 should be taken at Lower St. Anthony Falls Dam, and stage data for Reach #4 should be taken at Lock and Dam #1.

Discharge

Pool stages must be correlated to volumetric discharge in order to develop a water balance sheet for the MWMO, and before pollutant loadings can be calculated from water quality concentration data. The USACE has measured daily and 8-hour discharge data at Lower Saint Anthony Falls and Lock and Dam #1. Correlating stage depth to volumetric discharge requires the measurement of stage-discharge relationships over a range of flow levels in order to develop a rating curve for each flow measurement location. The USACE will be able to provide these stage discharge curves at the dam locations. Correlating discharge between reaches requires further study regarding groundwater and surface water inputs to the river. A flow contributions study can provide the information necessary to answer this question further.

The USGS operates a continuous flow gage (#05288500) at RM 865 near Anoka; no major tributaries enter the Mississippi below this gage and above the MWMO. The MWMO should verify the assumption that flows at #05288500 (Point A) can used as a proxy for the flow entering the MWMO (Point B). This assumption can be made if little flow is added to the Mississippi between A and B (e.g., from ephemeral stormwater outfalls) and/or the error associated with measuring a big river using hand-held flow meters is greater than the uncertainty between flow A and flow B.

Water Quality

Water quality parameters can change as the river traverses through the four reaches. These changes could be minimal, such as the case of a conservative element like chloride, or the changes could be substantial, such as dissolved oxygen as it passes over the dams/falls. Parameters, such as dissolved oxygen, can in turn influence aquatic and biotic processes that could affect other pollutants.

It is recommended that the MWMO first identify which pollutants are of the most interest to them as an organization, next define the scope of the concern, and then determine if the data desired needs to be at a scale such that reach-by-reach values and/or dynamics must be monitored and documented. Once the parameters of most importance and the scale are determined, the likely impact of the different reaches can be assessed. Until then, the number of variables potentially affecting different water quality parameters are too numerous and interconnected to generalize here.

Field parameters (T, pH, DO, SC)

Water quality parameters that are sensitive to environmental setting and must be measured in situ are sometimes spatially and/or temporally dynamic and at other times are not. In a large river like the Mississippi, temperature and pH tend to vary less than dissolved oxygen (DO) and specific conductance (SC), which are more sensitive to turbulence and mixing patterns. The MWMO should monitor all four measures of field conditions for each reach where monitoring is occurring, but the latter (DO and SC) are expected to show greater variability throughout the MWMO stretch of the Mississippi River. With respect to industrial outfalls, NPDES discharges could affect temperature and pH; the long-term (1976-2005) spatial trends in MCES data indicate a slight warming within the Mississippi River, from 12.9 ºC upstream of the MWMO to 13.3 ºC downstream of the MWMO (Lafrancois et al., in development). Monitoring immediately upstream and downstream of key industrial outfalls would give better spatial resolution to temperature changes that may be influencing aquatic health in the river.

Sediments and turbidity

In terms of sediment sources, streambank erosion in this stretch of the river is not expected to be a major sediment source on such a large, urbanized river as the Mississippi within the MWMO area. However, tributaries, stormwater outfalls, and the turbulence around lock-and-dam structures can be expected to create dynamic sediment concentrations within the river. It will be important for the MWMO to identify the location and relative contributions of all significant sources of sediment to the river, and data should not be extrapolated from reach to reach.

Nutrients

A discussion of nutrients is included here, especially due to the Lake Pepin Eutrophication TMDL. In the near future, the MWMO can expect to see load and wasteload allocations attributed to the MWMO subwatershed. It will be helpful to identify the locations and relative contributions of sediment and nutrient sources in this stretch of the river, particularly from surface runoff pathways, including the two major tributaries in Reaches #1 and #2, Shingle Creek and Bassett Creek, and the multitude of stormwater outfalls that populate all four reaches. Due to the quantities of these inputs throughout the river, nutrient data should not be extrapolated between reaches.

Bacteria

Bacteria data is not comparable between reaches due to the various inputs of bacterial sources throughout the MWMO.

B. Mixing Considerations for Monitoring Protocol Development

Due to their influence on mixing processes, the big river characteristics (BRCs) listed in Section II.B. will also have an effect on protocol development and the sample design process. In particular, aspects of a given BRC, when combined with other BRCs, will alter mixing behavior, depending on the parameter and speed of mixing processes, having implications for the MWMO's monitoring design requirements. Tables 7a and 7b summarize these implications, which are discussed in greater detail in the sections below (IV.C. and IV.D.).

Table 7a. **BRCs with unknown or uniform distribution across the MWMO reaches**, discussed in Section IV.C. The potential influence of big river mixing characteristics (BRCs, from Section II.B), alone or in combination with another BRC, on water quality outcomes and the implications for protocol development.

BRC (or aspect)	+ Another BRC	= Outcome	Implications for Protocol Devt.
Precip. (annual var.) (intensity)		Annual extremes	Return period
	Land use	Speed of runoff	Sampling frequency
Flowrate		Pollutant distribution	Site location & num.
Extremes (flood) (drought)	Flow rate	Speed of runoff	Sampling frequency
	Primary Prod.	Algal blooms	Parameter selection
Groundwater	Land use	Pollutant types	Parameter selection
	Pollutant properties	Speed of runoff	Sampling frequency
Ice	Field conditions	Pollutant distribution	Sampling frequency
Wind	Pollutant properties	Pollutant distribution	Site location & num.
Field parameters	Primary Prod.	Pollutant distribution	Parameter selection Site location & num.
Pollutant properties	Flow rate, substrate	Pollutant distribution	Site location & num.
Substrate		Pollutant distribution	Parameter selection Return period
Susp. seds	Flow rate	Pollutant distribution	Sampling frequency
	Primary Prod.	Algal blooms	Parameter selection
Nutrients	Pollutant properties	Pollutant distribution	Site location & num.
	Land use	Pollutant types	Sampling frequency
Riparian vegetation		Pollutant distribution	Site location & num.
Primary Prod.	Land use	Algal blooms	Parameter selection
Storm outfalls	Land use	Speed of runoff	Parameter selection Site location & num.
WWTP		Pollutant distribution	Site location & num.
Land use	Flow rate (low)	Algal blooms	Parameter selection
	Precipitation	Speed of runoff	Sampling frequency
Wing dams		Pollutant distribution	Site location & num.
Weirs	Pollutant properties	Pollutant distribution	Site location & num.

Table 7b. **BRC with known distributions across the MWMO reaches**, discussed in Section IV.D. The potential influence of big river mixing characteristics (BRCs, from Section II.B), alone or in combination with another BRC, on water quality outcomes and the implications for protocol development.

BRC (or aspect)	+ Another BRC	= Outcome	Implications for Protocol Devt.
Elevation (gradient)		Speed of runoff	Sampling frequency
Tributaries	Land use	Pollutant types	Parameter selection
	Flow rate (ratios)	Pollutant distribution	Site location & num.
Ch. morphology		Pollutant distribution	Site location & num.
Islands		Pollutant distribution	Site location & num.
Dead zones		Pollutant distribution	Sampling frequency
Indus. outfalls	Field conditions	Stratification	Site location & num.
Appropriations		Pollutant distribution	Site location & num.
Vessels	Flow rate (low)	Pollutant distribution	Site location & num.
L&Ds	Field parameters	Pollutant distribution	Site location & num.
Bridges		Pollutant distribution	Site location & num.

C. Mixing Considerations for Monitoring Protocol Development within All Four Reaches

The big river characteristics that influence mixing in all four reaches described in Section II.D will also influence the development of monitoring protocols. This section discusses these protocol considerations as they apply to all four reaches.

Selection of Monitoring Parameters

Monitoring budgets are always finite, and no agency can afford to sample for all possible monitoring parameters. For starters, the MWMO may want to focus on water quality parameters that have triggered an impaired status listing for a water body upstream, within, or downstream of the MWMO area (see Table 2), with particular focus on sediments and nutrients. In addition, the MWMO may want to consider selecting monitoring parameters that reflect the land use of its contributing area (i.e., expected pollutants from an urban residential and industrial landscape) that could either be delivered through flashy runoff via stormwater outfalls or tributaries, or delivered by base-level groundwater discharge. Finally, the MWMO may want to consider an adaptive monitoring approach that monitors select parameters during flood or drought conditions. Extremely low-flow conditions alter the hydraulic and pollutant mixing behaviors of a big river to the degree that warrants focusing on a subset of monitoring parameters, especially dissolved oxygen, planktic and benthic algae, ammonia nitrogen, and phosphorus released from sediments.

Sampling Return Period

The nature of river systems is that they are sensitive to the annual variability of precipitation, and assessments of a river must include several monitoring years if the results are to be statistically meaningful. Even if the MWMO cannot afford to sample every site every year, the organization should plan on an intermittent return period for some or all sites, such as biennial (like NPS) or two out of five years (like MPCA). In addition to modified return periods for individual monitoring sites, the MWMO could economize by adjusting return periods for individual water quality parameters based in their variability in the natural environment. Some contaminants can persist in river substrates and fish tissue for decades; these parameters should be occasionally re-tested in large river systems.

Sampling Frequency

Sampling frequency is another aspect of sample design that issues from carefully thought-out monitoring questions; different monitoring goals require different sampling frequencies. Focusing on pollutants delivered by groundwater recharge or monitoring within low-flow dead zones may require lower frequency sampling. In contrast, climate variability and land use alterations can indicate the need for higher frequency sampling. Rainfall intensity, when combined with impervious land surfaces and higher elevation banks, enhances the speed of runoff. Extremely high-flow conditions cause wide fluctuations in hydraulic and pollutant mixing behaviors in rivers, requiring more frequent sampling in order to assess both chronic and acute ecological degradation.

To support the TMDL process, the MWMO should consider increasing its ability to calculate annual loads at monitoring stations in which it has an interest, especially at the top (RM 859) and bottom (RM 848) of the MWMO area and at key source inputs (tributaries or outfalls). Calculating annual loads from a monitoring site requires continuous flow monitoring and both background sampling (i.e., monthly) and composite event sampling during several storm events per year, for a total of 20-30 samples per year (e.g., MCES 2003). Making the step up from background sampling to event sampling can entail an order of magnitude (from 2- to 10-times) greater monitoring effort for a monitoring agency. It is a non-trivial, albeit very important, undertaking.

Site Selection Method

All four reaches are relatively small, having lengths of 1.2, 3.7, 0.7, and 5.6 river miles. The USEPA-EMAP approach of statistically-random-sampling for site selection is appropriate for broad environmental characterization of major basins. In this densely-populated urban area, where there are a large number of big river characteristics that influence mixing within the relatively short reaches, a random-sampling design is not appropriate. The USGS and MPCA approaches of characterizing the influence of land use on water quality and targeting site selection for known pollutant sources seems more appropriate for the MWMO watershed. If the MWMO desires to characterize the overall condition of the Mississippi River within the entire MWMO area, it should consider random sampling of its entire reach (from a statistically-valid number of sites, determined by monitoring parameter variance), no matter within which of the four reaches the random sites happen to land.

Number and location of sites

The number and location of sites depend on the details specified within the monitoring goals and questions. If the monitoring focus is on physical mixing processes, which dominate in high-flow conditions, more sites may be necessary than when the focus is on chemical or biological mixing processes, which dominate under low-flow conditions. The influence of anthropogenic mixing characteristics can also become more important under low-flow conditions, notably vessel traffic and land use runoff. In the case of heated industrial discharges, the MWMO should look for thermal stratification that interferes with vertical mixing.

The number and location of sites are largely a function of the expected spatial distribution of the pollutant(s) of interest. Depending on the properties of a pollutant, its spatial distribution may be clustered (e.g., in particular depositional environments) or widespread throughout the entire river system. Knowledge about how different ions function in the natural environment can inform the placement of monitoring sites. Even when focusing solely on nutrients, some nutrients (i.e., phosphorus) travel attached to sediment particles and are subject to particle deposition, while other nutrients (i.e., nitrate-nitrogen) travel unencumbered by sediments.

Depending on the monitoring goals of the MWMO, it may want to determine whether the number and placement of current monitoring sites maintained by other agencies is sufficient to characterize the natural resource and to identify the sources of ecological degradation. For example, the MWMO should determine whether the monitoring parameters and frequency of sampling conducted by the NPS, MPCA, and MCES for the municipal intake at RM 862.8 is sufficient to characterize the inputs at its northern boundary. In addition, the MWMO should consult with representatives from other monitoring agencies to determine whether they can collaborate on shared monitoring goals, thereby extending each other's monitoring budgets and building cooperative relationships.

Mixing Influence versus Mixing Outcome

Evaluating the Mississippi River for mixing characteristics will determine site locations depending on whether the focus is the influence or the outcome of mixing processes. Monitoring for the influence of potential pollutant sources (i.e., tributaries, outfalls) should be done using a single site at the mouth of the pollutant source before it is injected into the Mississippi, to enable comparison with water quality in the mainstem river. Monitoring for the outcome of a given mixing process on Mississippi River water quality should be conducted sufficiently downstream to ensure complete mixing, and is best conducted using several sites at a cross-section to test for vertical and lateral mixing. This analysis is strengthened when the same cross-sectional monitoring technique is applied to an upstream site for comparison with the downstream outcome.

Identifying mixing outcomes by paired comparison between nearby upstream and sufficiently downstream sites or cross-sections is most applicable to river mixing characteristics that are few in number and spatially discrete (e.g., NPDES industrial outfalls, dams, bridges). Once the outcome of these few discrete characteristics are understood, based on monitoring data collected over a range of flows, then the outcomes due to the remaining characteristics can be estimated by subtraction. That is, by looking at loading at the top of the MWMO and loading at the bottom of the MWMO, one can determine the change in Mississippi River loading as it flows through the MWMO. Subtracting the outcomes or changes due to the few discrete characteristics (e.g., NPDES industrial outfalls, dams, bridges), would yield a remainder that could be assigned to those remaining characteristics that are too numerous or nonpoint to be measured individually (e.g., atmospheric deposition, changes in the elevation gradient, groundwater discharge, stormwater outfalls, variability in land use).

Making use of bridges

The placement of a site for the purpose of sampling from the centroid of flow can depend on channel geometries, meanders, and islands, and on the placement of bridges. Bridges are a favorite monitoring access location for USGS river monitoring personnel, due to the convenient and safe access to the centroid of flow (or near to it, depending on the placement of bridge piers). In this respect, the MWMO is blessed with nearly 20 bridges along a stretch of 11.2 river miles. However, the bridges in Reach #4 are all over 50-feet above the river, rendering them impractical for sample collection access points. The remaining 10 bridges in the upper MWMO should be reviewed for the presence of bridge piers in the river and, in our judgment, bridge locations with minimal piers disturbing flow in the river would be appropriate sampling points. For quality control, samples should be collected on the upstream side of the bridge to avoid road contaminants and river turbulence. For safety, traffic cones should be employed.

D. Mixing Considerations for Monitoring Protocol Development within Individual Reaches

The big river characteristics that influence mixing in each reach described in Section II.D (summarized in Table 8) will also influence the development of monitoring protocols. This section discusses these protocol considerations as they apply to each reach individually.

Table 8. Summary of Big River Characteristics within Individual MWMO Reaches.

Big River Characteristic	Reach 1	Reach 2	Reach 3	Reach 4
Elevation above banks	✓	✓	✓	✓
Tributaries	✓		✓	
River channel morphology	✓	✓	✓	✓
River islands	✓	✓	✓	
Dead zones	✓	✓	✓	✓
Industrial outfalls	✓	✓		✓
Water appropriations	✓			
Lock-and-dams		✓	✓	✓
Vessel traffic		✓	✓	✓
Bridges	✓	✓	✓	✓

Reach #1 (RM 859.0 –RM 857.8):

Although this reach is relatively short (1.2 river miles), the channel morphology is shallow and wide, and well-mixed with respect to depth. The elevation gradient resulting from 40-feet high banks should produce less flashy runoff than the bedrock gorge sections of the river, requiring less frequent sampling. Flow in this reach should be less dynamic, and the water quality may be able to be characterized with fewer sampling points. Care should be taken to avoid sampling from potential dead zones on the streambank-side of the three islands. The MWMO may want to consider monitoring at the top of this reach for the water quality parameters that caused upstream reaches to be listed as impaired (see Table 2). Regulatory agencies (MDH and MPCA) can be expected to monitor for potential contamination of the water supply intake immediately upstream of the MWMO area, and NPS and MCES also monitor at that location (RM 862.8). The MWMO needs to determine whether the data collected by these agencies sufficiently answers the question "What is the water quality of the Mississippi River as it enters the MWMO?" The assumption by those agencies, that the Mississippi River is sufficiently mixed to warrant a single sample from the centroid of flow, should be verified or refuted, by intensive simultaneous sampling across a cross-section of the river. To calculate the annual loads of contaminants entering the MWMO, the organization will need to sample the Mississippi during storm events and estimate the loading from unsampled storm events. In conjunction with this effort, the MWMO should explore collaborating with the USGS to install an ADVM flow gage on a bridge near the top of the MWMO. The compositions and flow volumes of the Minneapolis Water Works NPDES outfalls should be determined and taken into account when interpreting monitoring results in this reach. If industrial discharges are heated, the MWMO should look for thermal stratification that interferes with vertical mixing. Sampling for this reach of the Mississippi should be done upstream of the Shingle Creek tributary entering the river at RM 857.9.

Reach #2 (RM 857.8 – RM 854.1):

This reach is relatively longer (3.7 river miles), narrowing within the beginnings of the bedrock gorge as it winds its way toward the Upper St. Anthony Falls Dam. The dam serves to raise the natural water elevation and decrease the bank height; this should cause less flashy runoff than Reach #1, but an increasing proportion of impervious area as this reach enters the downtown Minneapolis area probably cancels-out the effect. Two major tributaries enter this stretch of the river, Shingle Creek at the top of the reach (RM 857.9) and Bassett Creek near the bottom of the reach (RM 854.7). The MWMO may want to consider monitoring from the mouths of these tributaries for the water quality parameters that caused these tributaries to be placed on the 2006 Impaired Waters List (see Table 2). These are highly-urbanized tributaries with potential for surges in flow. The site selection process would warrant some investigation on the influence of those inputs, such as mixing zone characteristics within the Mississippi River under a range of low, average, and high river flow conditions. Interference from barge traffic during sampling becomes a safety concern in this reach. However, care should be taken to avoid sampling from potential dead zones in the channels east of the islands and behind the dam. Information regarding the flow volume and composition of the XCEL industrial outfalls in this reach should be obtained to help interpret monitoring results below RM 856.6. If industrial discharges are heated, the MWMO should look for thermal stratification that interferes with vertical mixing. The MWMO may want to consider monitoring below the outfalls and tributaries (approximately RM 855, near Boom Island and Plymouth Avenue Bridge) as the Mississippi enters the down town area, but above the influence of the St. Anthony Falls dams.

Reach #3 (RM 854.1 – RM 853.4):

Although this is an extremely short reach (0.7 river miles) between the Upper and Lower St. Anthony Falls Dams, reservoir conditions are expected to be highly turbulent and dynamic, particularly in the central and west-bank portions of the river. As the river level drops 40 feet downstream of the upper dam, the elevation of the banks above the river increases to 70 feet, enhancing dynamic surface runoff from surrounding areas. Care should be taken to avoid sampling from potential dead zones in backwaters near Hennepin Island and behind the Lower dam. Vessel traffic will be heavy on the west side of the river between the upper and lower locks and negligible in the rest of the river.

Reach #4 (RM 853.4 – RM 847.8):

This longer reach (5.6 river miles) is deeply incised within a bedrock gorge. The bridges in this reach are too high above the river to serve as useful sampling access points, and monitoring should be conducted from motorized boats. After another 30-foot drop in water elevation at the Lower dam, this reach can be characterized by a very narrow channel that winds past the University of Minnesota and the historic portage site of Father Hennepin, widening as it nears the lower portions of Pool #1. Flow is likely turbulent below the Lower St. Anthony Falls dam, and around the piers of the several bridges. Care should be taken to avoid sampling from a potential dead zone behind L&D#1. This reach contains four NPDES discharge permits (at RM 850.4, 849.0, 848.0, 847.9), and information regarding the composition and flow volume of the industrial outfalls in this reach should be obtained to help interpret monitoring results. If industrial discharges are heated, the MWMO should look for thermal stratification that interferes with vertical mixing. In addition, this reach is on the 2006 Impaired Waters list for fecal coliform bacteria; the source(s) of this contaminant needs to be identified as part of the TMDL development process. Vessel traffic will occur throughout this reach and should be taken into account when interpreting monitoring results. Similar to Reach #2, the MWMO may want to consider monitoring below the St. Anthony Falls dams (approximately RM 852 – 850). Similar to Reach #1, the MWMO may want to evaluate whether the data collected by NPS and MCES is sufficient to answer the question “What is the water quality of the Mississippi River as it leaves the MWMO?” The assumption by those agencies, that the Mississippi River is sufficiently mixed to warrant a single sample from the centroid of flow, should be verified or refuted, by intensive simultaneous sampling across a cross-section of the river. To calculate the annual loads of contaminants leaving the MWMO, the organization will need to sample the Mississippi during storm events and estimate the loading from unsampled storm events. In conjunction with this effort, the MWMO should explore collaborating with the USGS to install an ADVM flow gage on a bridge near the bottom of the MWMO.

V. Mixing and Monitoring Protocol Gaps

Recommendations in this section highlight the primary gaps in data that exist in the MWMO in regards to both hydraulic mixing research and monitoring protocols, and provide an approach to fill the gaps.

A. Methods to Fill Hydraulic and Pollutant Mixing Data Gaps

Gap #1

There is no site-specific data or model to address mixing in the MWMO's stretch of the Mississippi River:

The MWMO contains many features that influence big river mixing, and yet monitoring agencies assume that the waters of the Mississippi River are mixed enough to be represented by a single mid-river sample.

Is the water quality of the Mississippi River within the MWMO more diverse than expected due to hydraulic mixing dynamics from a multitude of pollution point sources (outfalls and tributaries), and therefore does adequate monitoring of river water quality require more than a single depth-integrated sample at the centroid of flow?

Throughout the research literature investigated for this report, no mixing studies were identified that have been conducted within the MWMO reach. The largest mixing data gap is mixing data specific to reaches of the MWMO. No reliable method of approximation or use of proxies exist for identifying site specific mixing regimes without undertaking a tracer study and creating a model.

Recommendation #1

To fill the mixing data gaps we recommend that the MWMO (1) complete a tracer study and mathematical model or physical model, and (2) complete a flow contributions study. In addition, qualitative and quantitative mixing assessments could be undertaken.

Mixing Study - Tracer Study and Mathematical Model

A mixing study (tracer study and mathematical model) will explicitly define the origin of the water at potential monitoring locations allowing the MWMO to be confident that the monitoring data is being correctly correlated to the source of the water. The key advantage of creating a model is that many different scenarios can be analyzed without conducting the study on the river itself, which is significantly more expensive. The effects of different flow conditions, appropriations and dam operations can all be simulated.

A tracer study provides critical information for any type of quantitative mixing analysis. Particularly, a tracer study can provide longitudinal and transverse mixing coefficients, which are highly sensitive components that are difficult or impossible to estimate accurately. A tracer study would also provide information about the vertical mixing occurring in the water column. Although some proxies for a tracer study were examined, it is highly unlikely that using one of these methods to estimate mixing parameters in the MWMO reach would provide accurate enough data to be worthwhile.

Options for tracers include fluorescent dye tracers and sulphur hexafluoride (SF_6) tracers. For a large river such as the Mississippi, we recommend using SF_6 for its proven accuracy in big rivers and cost-effectiveness (Caplow 2004). Tracer studies in big rivers can be very costly (>$100,000). Some critical issues to address when undertaking a mixing study include:

- Spatial distribution at release point
- Mixing of tracer at release point
- Loss of tracer during mixing study
- Stationing of field sampling equipment
- Sufficient measurements over space and time
- Long tail of tracer during mixing study

For a mathematical model, we recommend a 3-dimensional mixing model that would use information collected from the tracer study to quantify the mixing occurring in different reaches of the Mississippi. Many of the common software programs associated with river water quality and hydrodynamics are insufficient to analyze the type of information in which the MWMO is interested.

The models CE-QUAL-W2, EFDC and CORMIX are three of the more common software packages that were examined for this report. In addition, many other models were encountered throughout the research. Each of them has drawbacks that prevent them from accomplishing the MWMO's goal. The EFDC hydrodynamic model (US EPA 2002, US EPA 2006) appears to be the most capable model examined, although no case studies regarding using it in combination with a tracer study to set up a monitoring plan were reviewed. We recommend that the MWMO further investigate the use of these models as the first step in creating a river model. This mixing information would provide a very detailed depiction of the mixing occurring in the MWMO. It is recommended that conducting a tracer study should be undertaken to provide information to the model instead of using literature values of mixing parameters. Creating mathematical models can be a costly effort and the level of detail required often dictates the total cost. Further research and a work plan would be necessary to estimate the total cost of undertaking this project.

Physical Model

A 1:200-scale physical model of the MWMO created at University of Minnesota's St. Anthony Falls Laboratory provides many of the benefits of a mathematical model; primarily the ability to run through a large range of river discharges and flow scenarios for a relatively low cost per scenario. As with the mathematical model, the high initial cost is a downside to this approach (>$100,000).

Flow Contributions Study

A flow contributions study should provide a good overview of the inflows and outflows that comprise a water balance for the MWMO area. This basic level of understanding of how water moves through the MWMO is a critical first step to help guide the monitoring program. This study would, to the extent that data is available to support it:

- Provide a water balance of the inflows and outflows over a given time period
- Provide a measure of relative contributions within the MWMO
- Allow for the comparison of timing of local and regional flows
- Evaluate the river under low, average, and high flow conditions
- Allow for a mass balance of pollutant inflows and outflows

Qualitative Mixing Assessment

A qualitative mixing study could add to a flow contribution study by using available data and field observation to describe mixing within each reach. This would include boat tours to determine surface flow streamlines under different flow rates.

This type of study could provide information about the flow patterns at particular locations but requires more professional judgment to draw conclusions than a tracer study. This type of visual inspection primarily provides qualitative transverse mixing information, which in a relatively short reach (such as the Mississippi river through the MWMO) is the most important type of mixing to consider when setting up a monitoring plan. This approach requires a substantial knowledge base to interpret information correctly and should be used in coordination with a sample monitoring plan to verify results.

Quantitative Mixing Assessments

Quantitative mixing assessments at a given river cross-section entail an intensive sampling effort over a short period of time, preferably conducted simultaneously by several teams trained in consistent sampling methods, with each team assigned to a lateral position in the cross-section. Obviously, this could be an expensive project, depending on the number of monitoring parameters and the number of cross-sections measured. To stretch the monitoring budget, it is recommended to use a monitoring parameter that does not require laboratory analysis for each measurement. Some parameters can be quickly measured in the field using Hach kits or ion-specific probes, and multiparameter sondes can be used to measure *in situ* with depth. Care must be taken that a depth sampler is not causing significant flow disturbance, thus changing sample values. This monitoring effort should yield an assessment of the range of variability of a parameter at that location and time, and whether it meets the quantitative criteria for mixed waters (see section III.B.).

The characteristic variability of the Mississippi River water quality within the urbanized MWMO area is poorly understood. None of the regulatory monitoring agencies have taken it upon themselves to identify how the Mississippi changes through this 10 to 15 mile reach, or what may be causing those changes. The MWMO could help fill the spatial and temporal gaps in Mississippi River monitoring data by conducting a series of cross-sectional surveys along its reach of the Mississippi.

An important test of the mixing assumption is the comparison of the flow-weighted sampling method with the centroid sampling method at a site of one of the long-term monitoring agencies. The MWMO could conduct flow-weighted averaging of water quality sampling at sites upstream and downstream of the MWMO, using same sites as Metropolitan Council Environmental Services (RM 762.8 and RM 748.8). Effort should be made to coordinate sampling schedule (date and time) with Met Council river monitoring personnel (Scott Schellhaass) to enable direct comparison between MWMO's averaged water quality, MWMO's water quality at the centroid of flow, and MCES's water quality at the centroid of flow. This data would be most directly comparable if the MWMO contracted with MCES for laboratory analysis of the MWMO samples, thereby eliminating any bias introduced by differing laboratory methods.

Gap #2

There is no available literature that addresses the influence of the following big river characteristics on hydraulic mixing:

- Precipitation
- Elevation
- Groundwater discharges
- Substrate properties
- Suspended sediment
- Nutrient cycling
- Riparian vegetation
- Primary productivity
- Water appropriations
- Land use of the contributing area (watershed)

In addition, there is no available literature that addresses the influence of the following big river characteristics on pollutant mixing:

- River islands
- Ice cover
- Wind
- Dead zones
- Wing dams
- Bridges

Recommendation #2

Filling the gap in literature data regarding the general impact of these characteristics is probably unnecessary at this point. Any further investigations should be specific to the influence of specific characteristics in the MWMO. For example, instead of studying the effects that river islands have on pollutant mixing, study the effects of specific islands within the MWMO. If the MWMO has an extremely high interest in determining the relationship between any of the above big river characteristics and hydraulic or pollutant mixing, they could contract with a qualified hydrologic researcher to develop the necessary analytical approach and data.

B. Methods to Fill Monitoring Protocol Gaps

In contrast with the analytical techniques for hydraulic mixing, methods for water resource monitoring have long been established. The USGS has been flow gaging since 1888, and concerns about water pollution in the 1970s prompted the development of water sampling and analysis techniques, with an emphasis in recent decades on quality assurance and control. However, as human technologies continue to advance, so do new techniques for every stage of monitoring protocol development:

- New pollutant parameters of emerging interest and increased capability of detection
- New sample collection technologies (e.g., water quality sensor nets in the flow cross-section)
- New data management and access capabilities
- New reporting modes and venues (e.g., on-demand internet capabilities)

VI. Annotated Bibliography User's Guide

A. Background and Format

Appendix A is the annotated bibliography of materials reviewed for this report. The bibliography consists of two sections: hydraulic mixing and monitoring protocols. Local conditions papers were also reviewed for this project. Most materials are available in electronic format although some are available as hard copy only and reside with the MWMO. The papers in the annotated bibliography were compiled from relevant mixing and monitoring searches of peer-reviewed journals, governmental reports, university studies, and private reports. Internet, library, and governmental searches were used to find papers relevant to the goals of the project.

Annotations are listed by lead author and date. The first annotation in each bibliography section provides a description key of the information that can be found within each annotation.

B. Cross-Referencing Tables with Annotations

Four tables are included to help organize the information within the annotated bibliography (Appendix A).

Table 1 organizes the references addressing big river characteristics. This table is most helpful when looking for information regarding a particular river characteristic. The table will refer to an annotation that can then be reviewed for relevant information. If additional information on the topic is desired, individual papers can be more thoroughly reviewed.

During the literature review much information regarding the theoretical aspects of mixing were recorded. These papers often incorporated models, equations, dispersion coefficients, and field tests into the description of mixing in big rivers. Table 2 can be used with the annotated bibliography to find the correct paper to research a particular theoretical component of river mixing.

Table 3 contains references that pertain to local conditions papers. Local conditions papers give background information on the MWMO reach of the Mississippi River that is relevant to mixing or monitoring. The table summarizes local conditions papers using the categories of big river characteristics: physical, chemical, biological, and anthropogenic.

Due to the quantity of information available on the Mississippi River produced by the U.S. Army Corps of Engineers, all local conditions information from the COE was not included. If a more complete collection of local conditions studies is desired, further investigation is possible. (Contact COE librarian Jung-Ae Kim at 651-290-5680.)

Table 4 lists the contact personnel for proposed mixing and monitoring projects.

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Fischer, H.B., List, E.J., Koh, R. C.Y., Imberger, J., and Brooks, N.H. (1979). Mixing in inland and coastal waters. Academic Press, 483 pp.

Jury, W.A., Gardner, W.R., and Gardner, W.H. (1991). Soil physics—5th edition. John Wiley and Sons, Inc., 328 pp.

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MWMO (2006). Amended Version of Watershed Management Plan. Mississippi Watershed Management Organization, Minneapolis, MN, 163 pp.

Stumm, W. and Morgan, J.J. (1981). Aquatic Chemistry – An introduction emphasizing chemical equilibria in natural waters – 2nd edition. John Wiley and Sons, Inc., 780 pp.

Appendix A. Annotated Bibliography and Tables

Hydraulic Mixing Annotated Bibliography

Bibliography contains complete citations for each document, plus the following information:

Source and purpose: Type of report/paper, and purpose

Summary of tools used to determine hydraulic mixing: If the paper only addresses local conditions (and not hydraulic mixing specifically), this field will be NA.

Summary of results as they relate to hydraulic mixing and setting: If the paper only addresses local conditions (and not hydraulic mixing specifically), this field will be NA.

Summary of river conditions within MWMO: A local conditions paper is one that specifically addresses conditions within the MWMO's reach of the Mississippi River. If it's a local conditions paper, this field will be filled in and the reference will be listed in the local conditions table. If it's not a local conditions paper, this field will be NA.

Applicability to Mississippi River: Low/Moderate/High, and why (applicability to MWMO's stretch of Mississippi River)

Summary of how river characteristics are affecting hydraulic mixing and time of travel: List of characteristics and explanation of how each affects hydraulic mixing and time of travel. Reference will be listed in Table 1 under applicable river characteristic.

Theoretical components: List of applicable theoretical components from Table 2.

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Arntson, A. D., Lorenz, D. L., Stark, J. R. (2004) Estimation of Travel Times for Seven Tributaries of the Mississippi River, St. Cloud to Minneapolis, Minnesota, 2003. U.S. Geological Survey Scientific Investigation Report 2004-5192. http://pubs.usgs.gov/sir/2004/5192/pdf/20045192.pdf

Source and purpose: This USGS Scientific Investigation Report (1) used regression equations to estimate travel times for three flow conditions (low, median and high) in seven tributaries of the Upper Mississippi River in Minnesota, (2) reports measurements of travel times in the Sauk River at median flow conditions using a dye tracer and (3) compares estimated travel times to measured travel times in the Sauk River to evaluate the estimation technique. Travel times were estimated for the leading edge, peak concentration, and trailing edge of tracer-response curves.

Summary of tools used to determine hydraulic mixing: The regression equations, which were developed by the USGS to estimate travel times, were solved using the following input: watershed drainage area, channel slope, mean annual discharge and instantaneous discharge at the time of measurement from more than 900 streams across the nation.

Summary of results as they relate to hydraulic mixing and setting: These equations give reasonable estimates of travel time for systems where storage is not a factor.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate – this report offers information for tributaries upstream of the MWMO. The information in this paper could be used to estimate time of travel for flows in other tributaries of interest to the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: This report marginally explains that drainage area, reach slope, mean annual river discharge, discharge at the time of measurement and the presence of pools, riffles, bends and other channel characteristics all affect the rate of longitudinal mixing. The report also marginally discusses the effect of storage areas such as lakes, marshes and backwater from dams, and acknowledges that the equations evaluated for this study are based on reaches where storage is not a factor.

Theoretical components: *Longitudinal dispersion coefficient.*

Baek, K. O., Seo, I. W., Jeong, S. J. (2006) Evaluation of Dispersion Coefficients in Meandering Channels from Transient Tracer Tests. J. Hydraul. Eng. 132(10), 1021-1032.

Source and purpose: Peer-reviewed journal investigating hydrodynamic influences on pollutant mixing in meandering channels.

Summary of tools used to determine hydraulic mixing: Flow and tracer experiments were conducted in an S-curved laboratory channel. In addition, a two-dimensional routing procedure was developed to evaluate both the longitudinal dispersion coefficient and the transverse dispersion coefficient based on the measured concentration data under the unsteady concentration condition. This routing procedure was developed without converting the governing equation of the unsteady condition to that of the steady condition. The laboratory setting was a meandering rectangular channel, 1 meter wide, 0.5 meter deep, and 15 m long.

Summary of results as they relate to hydraulic mixing and setting: Maximum velocity occurs along the optimum path of shortest travel distance through the bends allowed by the hydrodynamics.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low. The work in this paper is based on laboratory tests that marginally mimic the Mississippi River.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

River channel type: Meanders change the mixing characteristics by creating secondary currents and cause portions of the flow to lag. Meanders promote the separating and reemerging of tracer clouds.

Theoretical components: *Equations, Longitudinal dispersion coefficient, Transverse dispersion coefficient*

Beltaos, S. and Arora, V. K. (1988) Explicit Algorithm to Simulate Transient Transverse Mixing in Rivers. Canadian Journal of Civil Engineering 15(6), 964-976.

Source and purpose: Peer reviewed journal article investigating a better numerical solution to a transient transverse mixing model.

Summary of tools used to determine hydraulic mixing: This paper is theoretical and lab-based with a field verification in the Athabasca River below Fort McMurray, no information about the river or reach is reported.

Summary of river conditions within MWMO: NA

Summary of results as they relate to hydraulic mixing and setting: Using a model that employs an irregularly spaced grid with the length of each element equal to the time step times the local flow velocity may improve numerical problems involved with explicit solutions.

Applicability to Mississippi River: Low. This paper deals with the specific solutions to predict transient pollutant concentrations in the transverse mixing region and does not relate the finding to specific river characteristics.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

Dead zones: Where dead zones exist, a longitudinal concentration distribution will be a low-peak, long duration curve.

Theoretical components: *Equations, Longitudinal dispersion coefficient*

Beltaos, S. (1982) Dispersion in Tumbling Flow. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 108(HY4), 591-612.

Source and purpose: Peer reviewed journal intended to provide preliminary data on tumbling flow dispersion.

Summary of tools used to determine hydraulic mixing: Laboratory channel designed to mimic tumbling flow was created as a 1 m wide flume divided into 11 pools by triangular wears at 3 m intervals.

Summary of results as they relate to hydraulic mixing and setting: The paper concludes that conventional river dispersion models are a possible means of describing tumbling flow dispersion but it is unclear whether storage dispersion models are realistic.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: Tumbling flow may occur at the St. Anthony Falls Dam but it is highly unlikely that the results presented in this report would be applicable.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Weirs:* Create tumbling flow

Theoretical components: *Equations*

Boxall, J. B. and Guymer, I. (2003) Analysis and Prediction of Transverse Mixing Coefficients in Natural Channels. J. Hydraul. Eng. 129(2), 129-139.

Source and purpose: Peer reviewed journal investigating the longitudinal variation of the transverse mixing coefficient over a meander cycle.

Summary of tools used to determine hydraulic mixing: A new approach for predicting transverse mixing coefficients is developed using three input parameters, longitudinal planform curvature, cross-sectional shape, and total discharge. This method seems to under-predict the coefficient at high flows.

Summary of results as they relate to hydraulic mixing and setting: The transverse mixing coefficient is shown to exhibit considerable longitudinal variation over the meander cycle.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: The Mississippi in the MWMO reach has some meanders and this paper is the first to show that the rate of transverse mixing varies over the course of a meander.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

River channel type: Meandering channels have continually changing rates of transverse mixing

Theoretical components: *Equations, Transverse dispersion coefficient*

Boyle, J. M. and Spahr, N. E. (1985) Traveltime, longitudinal-dispersion, reaeration, and basin characteristics of the White River, Colorado and Utah. U.S. Geological Survey Water-Resources Investigations Report 85-4050, 54 p. \http://pubs.er.usgs.gov/usgspubs/wri/wri854050

Source and purpose: USGS study to determine traveltime and longitudinal dispersion characteristics for stream flow in designated reach of the White River for a range of discharge conditions

Summary of tools used to determine hydraulic mixing: Dye tracers were used in conjunction with regression equations.

Summary of results as they relate to hydraulic mixing and setting: The longitudinal dispersion coefficients ranged from 284 square feet per second at a discharge of 539 cfs to 3,560 square feet per second at a discharge of 1,580 cfs.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: The White River flows east to west from Colorado to Utah and outflows to the Green River. This river is 1-3 feet deep and flows between 281 to 1,840 cfs. Although this study was completed in a dissimilar river reach, it provides a good model for completing traveltime and longitudinal dispersion studies.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: Dispersion coefficients are not specifically attributed to river characteristics.

Theoretical components: Equations, Longitudinal dispersion, Field studies

Carr, L., Meridith and Rehmann, R., Chris (2007) Measuring the Dispersion Coefficient With Acoustic Doppler Current Profilers. Department of Civil Engineering, University of Illinois at Urbana-Champaign

Source and purpose: Received via email from author. Has been accepted to the Journal of Hydraulic Engineering but not yet published.

Summary of tools used to determine hydraulic mixing: Acoustic Doppler Current Profilers (ADCP) used primarily to measure flow rates were used to estimate the longitudinal dispersion coefficient (K) from velocities and bathymetry.

Summary of results as they relate to hydraulic mixing and setting: The ADCP measurements is at least as accurate as the best empirical formulas. Half of the estimates of K fall within 50% of the values from tracer studies, and 85% are within a factor of 3.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low. Using an ADCP to estimate K could be completed on the Mississippi. This method works best where shear dispersion controls mixing and where the water is vertically and transversely well-mixed. The rivers studied in this report included some rivers with similar flows to the Mississippi, particularly the Illinois River and the Missouri River.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: Dispersion coefficients are not specifically attributed to river characteristics.

Theoretical components: *Longitudinal dispersion, Equations*

Caplow, T., Schlosser, P., Ho, D. T. (2004) Tracer Study of Mixing and Transport in the Upper Hudson River with Multiple Dams. J. Environ. Eng. 130(12), 1498-1506.

Source and purpose: Peer reviewed journal comparing the behavior of a tracer in a river with dams to rivers without dams.

Summary of tools used to determine hydraulic mixing: A tracer experiment using SF6 in the non-tidal Hudson River.

Summary of results as they relate to hydraulic mixing and setting: This study indicates that pollutants become trapped in locks and are released as slugs when the water in the lock is released. It also found that the advection rate along the reach was constant due to increasing cross-sectional area that maintains a near-constant mean velocity.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low-Moderate: Many aspects of mixing in the Upper Hudson River have analogies to the Mississippi River as it flows through the Twin Cities. This stretch of the Hudson River has flows between 147 m^3/s and 385 m^3/s, similar to the Mississippi River, and includes locks and dams.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *River channel type:* As the cross sectional area in this reach increases with increasing flow, keeping the advection rate constant.

Lock and dam effects: Pollutants can become trapped in locks and will create a slug of pollutant concentration when the lock is drained. Dams also reduce the rate of longitudinal dispersion when compared to un-dammed rivers with similar flow rates.

Theoretical components: Longitudinal dispersion, Equations

Cheong, T. S. and Seo, I. W. (2003) Parameter estimation of the transient storage model by a routing method for river mixing processes. Water Resources Research 39(4), 1074.

Source and purpose: Peer reviewed journal exploring a new method of parameter estimation for the transient storage model.

Summary of tools used to determine hydraulic mixing: Results from a robust nonlinear equation solver were used to obtain a relationship between the mixing data and the terms in the functional relationship. This method compares the solution of the transient storage model to the observed concentration distribution in order to estimate the model parameters. This proposed method was validated in 33 US streams and appears to properly explain natural mixing processes in actual streams.

Summary of results as they relate to hydraulic mixing and setting: The concentration curves derived from the new method of parameter estimation provides a good match to the observed concentration curves.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: If a transient storage model is created this could provide a means of parameter estimation.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: Equations are not specifically attributed to river characteristics.

Theoretical components: *Equations*

City of Anoka (personal communication) Rum River Dam

Contact: Russ Zastrow, City of Anoka, 763-576-2782

Source and purpose: Personal communication (email) from Russ Zastrow from City of Anoka regarding operation of the Rum River Dam, there is no written manual.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low. The Rum River enters the Mississippi approximately 12 miles upstream of the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

City of Elk River (1982) Operation and Maintenance Manual: Elk River Dam (excerpt)

Source and purpose: The manual was prepared by the professional consulting engineering firm CH2M Hill.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low. Elk River enters the Mississippi approximately 25 miles upstream of the MWMO. Contains general dam information and rating curves.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

City of St. Cloud (1988) St. Cloud Hydroelectric Plant General Operations Manual (excerpt)

Source and purpose: Hydroelectric Plant Operations Manual. The St. Cloud Hydroelectric dam is an instantaneous run-of-river dam. The dam automatically maintains an upstream pool elevation of 981.0 feet. Any flows up to 6450 cfs are discharged through the turbines. Flows exceeding this value are diverted to an overflow spillway equipped with trip gates. The manual may be referred to for contacts at the St. Cloud plant.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low. The St. Cloud Hydroelectric Plant is located approximately 65 miles upstream of the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

Clark, J. F., Schlosser, P., Stute, M., Simpson, H. J. (1996) SF6-3He Tracer Release Experiment: A New Method of Determining Longitudinal Dispersion Coefficients in Large Rivers. Environ. Sci. Technol. 30(5), 1527-1532.

Source and purpose: Peer reviewed journal investigating use of a synthetic gas in place of dyes in large river studies.

Summary of tools used to determine hydraulic mixing: An SF6 tracer study in the tidal Hudson River.

Summary of results as they relate to hydraulic mixing and setting: SF6 tracer appears to be a good substitute for fluorescent dyes in large river systems. The main advantage of using SF6 to estimate dispersion coefficients in rivers is that it is much less expensive than fluorescent dyes. Daily mean gas transfer velocities can be determined by injecting 3He simultaneously with SF6.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: SF6 would be one alternative to consider if completing a time of travel study.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: Not discussed

Theoretical components: *Field studies*

Demetracopoulos, A. C. (1994) Computation of transverse mixing in streams. J. Environ. Eng. 120(3), 699-702.

Source and purpose: A peer reviewed journal investigating a method for the solution of advection/dispersion in natural streams.

Summary of tools used to determine hydraulic mixing: Numerical scheme utilizing either linear interpolation or an upwind scheme. The field data was collected in the Grand River in Kitchener, Ontario. The reach has an average width, depth, and velocity of 59.2m, 0.506m, and 0.353m/s, respectively.

Summary of results as they relate to hydraulic mixing and setting: The paper concludes that the depth-average form of the equation is unacceptable at sharp river bends. It also concludes that the data required of computation of steady-state-concentration distribution is an input-concentration profile, geometric information for each transect, and total river flow rate.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: Presents a method for longitudinal dispersion in natural streams but also realizes that it may not be reliable in reaches with highly irregular transects as may be encountered in the Mississippi.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *River channel type/geometry:* Using a depth-average mixing assumption at sharp river bends is unacceptable

Theoretical components: *Transverse dispersion coefficient*

Eheart, J. W. (1975) Application of Thermal Scanning to the Study of Transverse Mixing in Rivers. In: Proceedings of the NASA Earth Resources Survey Symposium, Technical Session Presentations, Water Resources. 2317-2324.

Source and purpose: This symposium discusses the application of remote-sensing to predict the two-dimensional movement of pollutants (BOD) in a river system.

Summary of tools used to determine hydraulic mixing: A mathematical model for the two-dimensional movement of pollutants in a river where complete mixing is assumed. The model is based on a mass balance. The temperature differences between the pollutant and the receiving water is exploited by applying a mathematical model of mass transport processes to heat transport and testing and calibrating it with thermal scanning.

Summary of results as they relate to hydraulic mixing and setting: Remote sensing may be effectively applied to the development of mathematical models for the two-dimensional movement of pollutants which do not exhibit a spectral signature.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High. This application could be applied to any river system, including the Mississippi River.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: *Equations, Transverse dispersion coefficients*

Elhadi, N., Harrington, A., Hill, I., Lau, Y. L., Krishnappan, B. G. (1984) River Mixing - A State-of-the-Art Report. Canadian Journal of Civil Engineering 11(3), 585-609.

Source and purpose: This peer-reviewed journal article is intended to be a reference document on river mixing to be used by anyone who is interested in obtaining a basic understanding of the mechanisms of transport and mixing as well as recommendations on how various types of mixing problems can be tackled.

Summary of tools used to determine hydraulic mixing: A description of the various physical processes involved in the spreading of a substance in river flows as well as the mathematical formulation of these processes is given. These processes are combined in the mass balance equation to describe the mixing of substances released into rivers. The difficulties of solving three-dimensional mixing problems for real river situations are discussed. The simplification of the equation into two dimensions using depth averaging and the introduction of the stream-tube concept are described. Analytical and numerical solutions are recommended. The effects of ice cover on mixing are discussed and cases of nonconservative substances are described. Field testing, types of tracers and the methodology of conducting dye tests in the field are discussed.

Summary of results as they relate to hydraulic mixing and setting: For three-dimensional mixing problems, it is concluded that the available analytical solutions are not very applicable to practical problems. Numerical modeling, including modeling of the flow field, will provide more accurate results. For the steady state problem involving the continuous release of a tracer, it is shown that the two-dimensional equation is applicable at some distance downstream for the source. By using the stream-tube approach, the equation can be simplified so that variations in river curvature, depth, and velocity can be taken into account. For the concentrations resulting from the release of a slug of material, it is shown that the traditional Fickian solution of the one-dimensional problem is often not applicable. A model is recommended that predicts different mixing behavior at different distances from the source.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low. While this article is very informative, it ranks low for the project as a whole due to its general nature. As stated above, this article is intended to be a reference document on river mixing. It provides the reader with a basic understanding of the processes and mathematical equations used to solve mixing problems in rivers.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

The physical parameters (river characteristics) that affect the mass balance equation are discussed in very general terms (e.g. the effect of channel curvature on secondary circulation, boundary conditions imposed by banks, etc.). This article also briefly touches on the effects of ice cover (addressed in more detail in subsequent articles by Lau) and mixing of nonneutral substances. The article does not address these characteristics enough to provide useful information regarding hydraulic mixing and time of travel.

Theoretical components: *Equations*

Gulliver, J. S. (2007) Introduction to Chemical Transport in the Environment. Cambridge University Press, England, chapters 5 and 6.

Source and purpose: Textbook chapters on turbulent diffusion and reactor mixing assumptions to be published in 2007.

Summary of tools used to determine hydraulic mixing: The textbook chapters explore many different mixing equations and assumptions, including complete mix reactor, plug flow reactor, dead zones, bypass, feedback, plug flow with dispersion, and complete mix reactors in series. The chapters also cover dispersion in groundwater flows and estimation of mixing parameters using tracer studies.

Summary of results as they relate to hydraulic mixing and setting: A useful paper for anyone wishing to understand the basics of mixing. No specific results are reported.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: Provides good information about the assumptions involved in reactor mixing although no details on the effects of physical parameters in rivers are given.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: Not discussed.

Theoretical components: *Equations, Longitudinal dispersion*

Hibbs, D. E. and Gulliver, J. S. (1999a) Dissolution rate coefficients for surface slicks on rivers. Wat. Res. 33(8), 1811-1816.

Source and purpose: Follow-up paper to “Processes controlling aqueous concentrations for Riverine spills”

Summary of tools used to determine hydraulic mixing: The water-film mass transfer rate coefficient was measured for the dissolution of a hexane slick in a stirred cylinder and in and oscillation grid chamber and also measured during reparation studies.

Summary of results as they relate to hydraulic mixing and setting: Results allow for easy prediction of the dissolution rate coefficient given the reaeration rate coefficient for a given river reach.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: Important for work specific to hexane slicks.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Trash/ Spills:* Applicable to mixing of oils spilled in rivers.

Theoretical components: *Equations:* Estimation technique of the dissolution coefficient for and aqueous concentration model.

Hibbs, D. E. and Gulliver, J. S. (1999b) Processes controlling aqueous concentrations for riverine spills. Journal of Hazardous Materials 64, 57-73.

Source and purpose: A companion paper to "An Aqueous Concentration Model of Riverine Spills" investigating the sensitivity of parameters used in the aqueous concentration model.

Summary of tools used to determine hydraulic mixing: The uncertainties in predicted aqueous concentrations are computed using a riverine spill model for a simulated spill of 10,000 kg of jet fuel.

Summary of results as they relate to hydraulic mixing and setting: The results indicate that the saturation concentrations and the dissolution rates are the most sensitive parameters and that the volatilization coefficient is the least sensitive. Furthermore, conflicting studies of the dissolution rate coefficient lead to an extremely high uncertainty in the values of the dissolution coefficient used in riverine spill models.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: The uncertainty and sensitivity of the spreading, evaporation, dissolution, volatilization and dispersion of an oil spill/leak could be important if a significant source is found within the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Trash/ Spills:* The saturation concentration and the dissolution rate of the oil are the most important factors to determining aqueous concentration and the impact on river biota.

Theoretical components: *Equations:* An aqueous concentration model is used to define the sensitivity of each input parameter.

Hibbs, D. E., Gulliver, J. S., Voller, V. R., Chen, Y. (1999) An aqueous concentration model for riverine spills. Journal of Hazardous Materials 64, 37-53.

Source and purpose: A peer reviewed journal developing a numerical model to predict aqueous concentrations of sparingly soluble compounds (oils).

Summary of tools used to determine hydraulic mixing: A numerical model is developed to predict the aqueous concentration of oils spilled into rivers. Processes simulated include spreading and drifting of the surface slick, evaporation, dissolution, volatilization, and longitudinal dispersion. The model assumes that the spilled substance dissolved in the water column or floating on the water surface is in the form of a slick.

Summary of results as they relate to hydraulic mixing and setting: Streamwise concentration gradients caused by the rapid evaporation of the more volatile compounds can have a significant impact on the resulting aqueous concentration during non-instantaneous riverine spills. A multiple-slick model in place of a single-slick model must be used to account for this evaporation

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low-Moderate: The model provides a method to deal with oil slick movement on rivers. The model is one-dimensional so it also assumes a well-mixed cross-section common in narrow, shallow streams and may not apply to large rivers.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Trash/ Spills:* An oil slick will move based primarily on the velocity of the water surface and the direction and magnitude of the wind.

Theoretical components: *Equations:* A single-slick and multi-slick equation are compared. It is shown that they are similar under short-duration spills and differ greatly under long duration spills.

Hibbs, D. E., Parkhill, K. L., Gulliver, J. S. (1998) Sulfur hexafluoride (SF6) gas tracer studies in streams. J. Environ. Eng. 124(8), 752-760.

Source and purpose: This peer reviewed paper investigates the use of sulfur hexafluoride (SF6) as a volatile tracer.

Summary of tools used to determine hydraulic mixing: The gas-tracer study was conducted in experimental channels at the Monticello Ecological Research Stations in central Minnesota and in the Nemadji River in northern Wisconsin.

Summary of results as they relate to hydraulic mixing and setting: The results conclude that SF6 is a valuable tool for use as a tracer in some small streams. SF6 can be measured very precisely due to its low level of quantification (LOQ).

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: The paper doesn't make any statements regarding the applicability to larger streams but Caplow et. al. (2004) used SF6 in the upper Hudson River which has similar flow characteristics to the Mississippi.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: Not discussed.

Theoretical components: *Field studies*

Ho, D. T., Schlosser, P., Caplow, T. (2002) Determination of Longitudinal Dispersion Coefficient and Net Advection in the Tidal Hudson River with a Large-Scale, High Resolution SF sub(6) Tracer Release Experiment. Environ. Sci. Technol. 36(15), 3234-3241.

Source and purpose: A peer reviewed journal to determine the longitudinal dispersion coefficient and net advection in the tidal Hudson River.

Summary of tools used to determine hydraulic mixing: A SF6 tracer experiment in the tidal portion of the Hudson River.

Summary of results as they relate to hydraulic mixing and setting: SF6 was successfully used as the tracer and a continuous sampling method that could be used in similar studies was used.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: The tidal influences in this study make the results less relevant to conditions in Minnesota.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: Not discussed

Theoretical components: *Field studies:* reconfirms the use of SF6 on a large scale water body.

Holley, E. R., Siemons, J., Abraham, G. (1972) Some Aspects of Analyzing Transverse Diffusion in Rivers. Journal of Hydraulic Research 10(1), 27-57.

Source and purpose: This peer reviewed journal article investigates factors that previously might have been lumped into the diffusion factor making it difficult if not impossible to find consistent correlations between such coefficients and simple physical parameters. Consideration is given to the variation of depth, longitudinal velocity and diffusion coefficient within the cross section and to transverse velocities. The depth-averaged mass conservation equation is presented to show how these factors enter the equation. Some numerical examples are given to illustrate the possible significance of these factors. Finally, a generalized change of moments method is derived to show how these factors may be included in calculating diffusion coefficients form measured concentrations.

Summary of tools used to determine hydraulic mixing: The depth-averaged conservation equation is used to estimate the possible significance of certain variables (page 6) and to derive the generalized change of moments method which accounts for these variables.

Summary of results as they relate to hydraulic mixing and setting: This article demonstrates that various factors (variable depth, variable diffusion coefficient, and transverse velocities) not normally considered may play an important role in transverse diffusion problems. In particular it is shown that transverse velocities in rivers may cause rates of spreading which are of the same magnitude as that due to diffusion.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low. The equations presented in this model may be used to calculate diffusion coefficients from measured concentrations.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: As stated previously, this article evaluates the affect of variable depth, variable diffusion coefficient and transverse velocities on transverse diffusion problems.

Theoretical components: *Equations, Longitudinal dispersion coefficient, Transverse dispersion coefficient*

Hunt, B. (2006) Asymptotic Solutions for One-Dimensional Dispersion in Rivers. J. Hydraulic Eng. 132(1), 87-93.

Source and purpose: This peer-reviewed journal article evaluates the use of three models in solving one-dimensional dispersion in a river from an instantaneous point source.

Summary of tools used to determine hydraulic mixing: One-dimensional dispersion in a river from an instantaneous point source is examined by using asymptotic solutions from three different models: (1) an asymptotic solution was obtained for the dead-zone equations first proposed by Hays (1966), (2) the second asymptotic model assumes that the dispersion coefficient increases with a power of time at large times after contaminant release and (3) the third model assumes that the dispersion coefficient increases with the first power of distance downstream from the point of contaminant release.

Summary of results as they relate to hydraulic mixing and setting: The second model is relatively simple, flexible and accurate and is recommended for use in describing one-dimensional contaminant dispersion in rivers.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: While this article provides a recommendation for the use of a model that describes one-dimensional contaminant dispersion in rivers, it was evaluated for a reach of the Monocacy River with the following characteristics: width of 49 m, a mean depth of 0.55 m, a mean velocity of 0.26 m/s, a bed slope of 0.0006, and a shear velocity of 0.052 m/s.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

Dead zones: This article looks at three different models to evaluate the impact of dead-zones on the one-dimensional dispersion of a pollutant in a river. Dead zones, or zones of transient storage, are zones of separated flow that can trap and/or release contaminants during the time period being evaluated.

Theoretical components: *Equations*

Jobson, H. E. (2001) Modeling Water Quality in Rivers using the Branched Lagrangian Transport Model (BLTM). U. S. Geological Survey Fact Sheet 147-00. HYPERLINK "http://water.usgs.gov/osw/pubs/FS-147-00.pdf" http://water.usgs.gov/osw/pubs/FS-147-00.pdf

Source and purpose: A USGS report on modeling of water quality using the Branched Lagrangian Transport Model (BLTM).

Summary of tools used to determine hydraulic mixing: The Branched Lagrangian Transport Model (BLTM) was developed by the U.S. Geological Survey to simulate the unsteady movement, dispersion, and chemical reactions for any number of dissolved constituents moving through a system of one-dimensional channels. Data requirements: Hydraulic – discharge, cross-sectional area, top width, tributary flow; General – number of branches, connecting junctions, distance, dispersion coefficient, initial concentration of each pollutant. Best suited for steep concentration gradients and highly variable flow.

Summary of results as they relate to hydraulic mixing and setting: No results discussed except examples.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: The BLTM could be a useful model if a water quality model was to be developed for the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: Specific river characteristics not discussed.

Theoretical components: *Modeling*

Jobson, H. E. (2000) Estimating the Variation of Travel Time in Rivers by Use of Wave Speed and Hydraulic Characteristics. U. S. Geological Survey, Water Resources Investigations Report 00-4187. HYPERLINK "http://pubs.er.usgs.gov/usgspubs/wri/wri004187" http://pubs.er.usgs.gov/usgspubs/wri/wri004187

Source and purpose: A USGS report describing a method of estimating travel time in rivers.

Summary of tools used to determine hydraulic mixing: Provides practical guidance on extrapolating travel-time information obtained at one flow to a different flow in the same reach of river. This paper offers two ways of estimating travel-time depending on the amount of available data, wave speed, and Manning's equation.

Summary of results as they relate to hydraulic mixing and setting: Wave speed is the preferred method and shown to be more accurate, but requires two gauging station along the river reach of interest.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High: Useful techniques to extrapolate travel-time information from one flow rate to another.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

Flow Rate: The flow rate measured at two stations on the same river reach can be used to measure the time of travel.

Theoretical components: *Equations*

Jobson, H. E. (1997) Predicting travel time and dispersion in rivers and streams. J. Hydraul. Eng. 123(11), 971-978.

Source and purpose: USGS paper providing a method of predicting travel time and dispersion of a slug injection in rivers where few data are available.

Summary of tools used to determine hydraulic mixing: This paper uses information compiled from a large number of time-of-travel and dispersion studies and presents empirical relations that appear to have general applicability. These findings should not be used in place of field studies.

Summary of results as they relate to hydraulic mixing and setting: The paper explains the theory of transport and dispersion of a slug injected dissolved pollutant such as a chemical spill. It also allows for estimates where only flow data and travel distances are available.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: Provides a good method of estimating travel times and dispersion on reaches that have very little available data and where fast results are more important than accurate results.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Trash/Spills:* Provides a method of quickly estimating the travel time and dispersion of a spilled contaminant.

Theoretical components: *Equations, Longitudinal dispersion coefficient*

Jobson, H. E. (1996) Prediction of Traveltime and Longitudinal Dispersion in Rivers and Streams. U. S. Geological Survey Water-Resources Investigations Report 96-4013. HYPERLINK "http://pubs.er.usgs.gov/usgspubs/wri/wri964013" http://pubs.er.usgs.gov/usgspubs/wri/wri964013

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Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Trash/Spills:* Provides a method of quickly estimating the travel time and dispersion of a spilled contaminant.

Theoretical components: *Equations, Longitudinal dispersion coefficient*

Johnson, T. R., and Stefan, H. G. (1987) Multiple Point Effluent Sampling At the Metropolitan Wastewater Treatment Plant (WWTP), St. Paul, MN. University Of Minnesota St. Anthony Falls Hydraulic Laboratory Project Report No. 262.

Source and purpose: University Of Minnesota St. Anthony Falls Hydraulic Laboratory Project Report 262 to determine the benefits of multiple transverse sampling points in the Metropolitan WWTP final effluent channel.

Summary of tools used to determine hydraulic mixing: A 1:12 sectional model was constructed at the St. Anthony Falls Hydraulic Laboratory. The sectional model assumes that the turbulent flow in the dechlorination basin depend primarily on vertical depth scales rather than horizontal ones.

Summary of results as they relate to hydraulic mixing and setting: (a) There appears to be a large difference between sampling at low and high tailwater stage. (b) To achieve similar representativeness, sampling duration can be reduced as the flow is increased when the tailwater is low. The reverse is true at high tailwater. (c) When high accuracy (deviations of 1 to 2%) is desired, sampling duration could be decreased when using more sampling points. If deviations of greater than 4% are acceptable, the sampling duration can be kept at 15 seconds or less to obtain a representative sample. (d) Mixing in the transverse direction is an important consideration when selecting the number of sampling points. 4 sampling stations appear to be sufficient. (e) The representativeness of a 1 second grab sample has been found to depend on tailwater elevation, flow rate and number of simultaneous sampling points. If one sampling point is used the deviation from the mean can be 7-22% , if 4 sampling points are used, the deviation drops to 4-6%.

Summary of river conditions within MWMO: The WWTP flows were examined at 175 mgd, 300 mgd, and 650 mgd.

Applicability to Mississippi River: Low: The study reports good information related to sampling frequency, location and expected deviation from mean. This model study was completed for a dechlorination basin, not for the river itself.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Flow rate:* Higher flows require shorter sampling frequency and/or more sampling points to achieve similar sampling accuracies.

Theoretical components: NA

Kahlig, P. (1979) One-Dimensional Transient Model for Short-Term Prediction of Downstream Pollution in Rivers. Water Research 13(12), 1311-1316.

Source and purpose: Peer reviewed journal describing a one dimensional pollution model.

Summary of tools used to determine hydraulic mixing: Kahlig presents a new routing procedure for river mixing.

Summary of results as they relate to hydraulic mixing and setting: The new routing procedure is compared to Fischer's previous work. Conditions necessary for this method include a large distance between measuring station and source.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: Presents a very basic and theoretical method for estimating one dimensional time of travel and dispersion based on Fischer's equations. Could be used as a reference if a time of travel study was conducted in the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: *Equations, Longitudinal dispersion*

Koltun, G. F., Ostheimer, C. J., Griffin, M. S. (2006) Velocity, Bathymetry, and Transverse Mixing Characteristics of the Ohio River Upstream from Cincinnati, Ohio. U. S. Geological Survey Open-File Report 2006-1159. http://pubs.er.usgs.gov/usgspubs/ofr/ofr20061159

Source and purpose: This USGS Scientific Investigation Report summarizes information that was gathered to parameterize hydrodynamic and water-quality models that are being developed for the study reach.

Summary of tools used to determine hydraulic mixing: Velocity, bathymetry and dye-concentration data were collected to parameterize hydrodynamic and water-quality models that are being developed for the study reach (34-mile stretch of the Ohio River extending from the lower pool of the Captain Anthony of the Licking and Ohio Rivers, near Newport, KY). Velocity data were measured using boat-mounted acoustic Doppler current profilers (ADCPs). Bathymetry data were measured by means of a boat-mounted single-beam echosounder. Two separate dye-tracer studies (using Rhodamine WT dye) were conducted to assess transverse mixing characteristics in the Ohio River.

Summary of results as they relate to hydraulic mixing and setting: Within the stream segments sampled, complete transverse mixing of the dye did not occur. Transverse mixing characteristics described in this report may not be representative of characteristics that would be observed for contaminants that are immiscible in water and/or have specific gravities that are much greater or less than that of water.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low. The hydrology of the study reach is very complex. Streamflows are regulated by the USACOE by managing dams upstream and downstream of the study reach, two large streams are tributary to the Ohio River within the study reach, and barges that use the river are a potential source of mixing that is variable and difficult to quantify (complicating the measurements and interpretation of the mixing characteristics).

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: *Transverse mixing coefficients, field tests*

Koussis, A. D. and Rodriguez-Mirasol, J. (1998) Hydraulic estimation of dispersion coefficient for streams. J. Hydraul. Eng. 124(3), 317-320.

Source and purpose: A peer reviewed journal that compares theoretical formulas to estimate the longitudinal dispersion coefficient for streams.

Summary of tools used to determine hydraulic mixing: Different methods of estimating the longitudinal dispersion coefficient from readily measurable hydraulic variables are explored. The estimates were compared to measured values in 16 streams including the Missouri and the Sabine.

Summary of results as they relate to hydraulic mixing and setting: The results show that the modified Taylor equation more accurately predicts longitudinal dispersion coefficients then the original equation in the streams researched. The specific data related to the larger rivers in the study indicates that the modified Taylor equation may be better at predicting dispersion coefficients than the original equation.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: This new formula is an update to the accepted Taylor formula. It is shown to provide closer estimates than the original formula. If a rough estimate of dispersion coefficient were desired, this would provide a good method to gain a starting estimation.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA: The assumptions that go into these estimations are not specific enough to attribute to specific river characteristics.

Theoretical components: *Equations, Longitudinal dispersion coefficient*

Lau, Y. L. (1985) Mixing Coefficient for Ice-covered and Free-surface Flows. Canadian Journal of Civil Engineering 12(3), 521-526.

Source and purpose: This peer-reviewed journal investigates which dimensionless mixing coefficient should be used for ice-covered flows.

Summary of tools used to determine hydraulic mixing: Dispersion experiments were conducted in southern Ontario on four river reaches under both open-water and ice-covered conditions. The data were used to obtain the transverse mixing coefficient and to investigate which dimensionless mixing coefficient should be used for ice-covered flows. The experiments consisted of injecting dye (Rhodamine B) at a constant rate into the river through a hole drilled in the ice and taking measurements of flow and concentration at a number of cross sections downstream.

Summary of results as they relate to hydraulic mixing and setting: Mixing coefficients were evaluated by comparing measured concentration profiles with those obtained from simulations using the model RIVMIX, which solves the mass conservation equation using the stream-tube concept. The transverse mixing coefficients showed almost no change in the values of the dimensionless coefficient e_z/U_*H between open-water and ice-covered conditions. It is recommended that, for calculating mixing in an ice-covered stream, the same value of e_z/U_*H as that for open-water conditions be used.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High. This article establishes a relationship between mixing coefficients that is applicable to any system being evaluated under ice-covered conditions.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

River channel type/geometry: The sinuosity of a river plays an important role in determining the value of the dimensionless mixing coefficient.

Ice flows and blockages: For systems that become ice covered, the velocity, shear stress, and diffusivity distributions are all changed substantially, all of which affect the mixing coefficients.

Theoretical components: *Equations, Field tests*

Lau,Y.L. and Krishnappan, B.G. (1981a) Ice Cover Effects on Stream Flows and Mixing. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 107(HY10), 1225-1242.

Source and purpose: This peer-reviewed journal evaluates the effects of ice cover on the flow and on the vertical mixing in rivers.

Summary of tools used to determine hydraulic mixing: In this paper, a procedure was out-lined to use the "*k-e*" turbulence model, described by Launder and Spalding, to calculate the depth, velocity distribution and the turbulent kinematic viscosity distribution for two flows with the same given discharge, bed slope, and bottom roughness. One of these flows has a free surface at the top while the other has an ice cover of a given roughness.

Summary of results as they relate to hydraulic mixing and setting: Results are used in the two-dimensional mass transport equation to simulate the concentration distributions due to sources placed at different heights in the flow (surface injection, middle injection and bottom injection). The results give some indications of the effects of ice cover on the flow and on the vertical mixing.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High. This article compares flow conditions in systems with a free surface to those with ice cover.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

Stormwater outfalls/pollutant point sources: Mixing characteristics were evaluated under a number of injection scenarios: surface injection, middle injection and bottom injections.

Ice flows and blockages: The presence of ice cover in a stream alters the flow characteristics – the normal flow depth increases due to increased resistance resulting from an additional solid boundary and the average flow velocity decreases. In addition, both the velocity and shear stress distributions change.

Theoretical components: *Equations*

Lau, Y. L. and Krishnappan, B. G. (1981b) Modeling Transverse Mixing in Natural Streams. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 107(HY2), 209-226.

Source and purpose: This peer reviewed article presents a numerical model based on the equation derived by Yotsukura and Sayre. The applicability of the model is tested using data from a field experiment. Simulations using different assumptions for the diffusion factor are compared. Finally the dependent of the transverse mixing coefficient on stream variables is investigated using published values for natural streams.

Summary of tools used to determine hydraulic mixing: The Yotsukura and Sayre equation is based on the stream tube or cumulative discharge concept and can account for changes in river geometry and curvature quite easily. This model allows one to use an analytical solution to obtain reasonable predictions for natural streams. For accurate simulations of transverse mixing in streams, one should use local values of uh^2m_x together with an average transverse dispersion coefficient. For streams with small curvatures, an estimate of the transverse dispersion coefficient can be made using published data presented in the article.

Summary of results as they relate to hydraulic mixing and setting: The results of the simulations performed during this study demonstrate that the cumulative-discharge model can simulate the transverse mixing in a natural stream satisfactorily.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: The numerical model could be applied to MWMO's segment of the river.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: *Equations, Transverse dispersion coefficient*

Lee, K. K. (1995) Stream Velocity and Dispersion Characteristics Determined by Dye-Tracer Studies on Selected Stream Reaches in the Willamette River Basin, Oregon. U. S. Geological Survey Water-Resources Investigations Report 95-4078. http://pubs.er.usgs.gov/usgspubs/wri/wri954078

Source and purpose: A USGS report summarizing a dye tracer study in the Willamette River Basin.

Summary of tools used to determine hydraulic mixing: A dye-tracer study of the Willamette river basin is conducted as part of a larger study in cooperation with the Oregon Department of Environmental Quality. This report documents stream-velocity and dispersion characteristics collected at several locations in the Willamette River Basin. The data collected was used to calibrate hydrodynamic and water quality models.

Summary of results as they relate to hydraulic mixing and setting: The paper defines a relation between velocity of the leading and trailing edges of the dye cloud to index locations along the reach.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: This stretch of the Willamette is a braided river and should not be compared to the Mississippi, although the methods used in the dye-tracer study provide a good model for conducting a dye-tracer field study.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *River channel type/geometry:* This paper generally says that pool-riffle effects and meanders affect the dispersive characteristics of a stream reach. It falls short of making any definitive statement about what those effects are.

Theoretical components: *Longitudinal dispersion coefficient*

Luk, G. K. Y., Lau, Y. L., Watt, W. E. (1990) Two-Dimensional Mixing in Rivers with Unsteady Pollutant Source. Journal of Environmental Engineering 116(1), 125-143.

Source and purpose: A peer reviewed journal describing a mixing model: Mixing Analysis Based on the Concept of Stream Tubes (MABOCOST)

Summary of tools used to determine hydraulic mixing: This is a numerical mixing model that can be used for the analysis of two-dimensional, transient mixing of nonconservative substances in natural streams. This model requires, in addition to hydrogeometric data, a transverse diffusion coefficient that may need to be obtained for any particular river reach.

Summary of results as they relate to hydraulic mixing and setting: The model was tested for a number of cases and solutions compare well to analytic solutions. The model was also tested in a laboratory experiment and performed well.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: The MABOCOST model demands a lot of input data including depth and velocity measurements and the transverse dispersion coefficient, which is difficult to accurately measure.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: *Transverse mixing coefficient, Equations*

Metropolitan Council (planned). Lower Minnesota River Project. http://www.metrocouncil.org/environment/Water/LMRM/index.htm

Contact: Cathy Larson, Metropolitan Council Environmental Services, 651-602-1275

Source and purpose: Metropolitan Council joint project with USGS to collect data to examine mixing in the MN River and how that might influence a water quality sampling program.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: The following data were collected:

Field measurements (temperature, DO, pH, conductivity, and turbidity) in 2003 and 2004 under six different flow regimes.

Field measurements (temperature, DO, pH, conductivity, and turbidity) and chemical parameters (nutrients and solids) in 2006.

As part of the 2006 sampling, samples were integrated both laterally across the channel and vertically, and these results will be compared to samples taken at discrete locations, to determine if the discrete samples are representative of the channel as a whole.

A water quality model (CE-QUAL-W2) is being developed for the MN River between Jordan and the confluence with the Mississippi River, and the monitoring data will be used for model calibration. The model will eventually be used for facility planning (by the Metropolitan Council) and for support of wasteload allocations in TMDL studies.

Applicability to Mississippi River: NA

Summary of how river characterisitcs are affecting hydraulic mixing and time of travel: NA

Theoretical components: Field Tests

Minnesota Pollution Control Agency (planned). Part two of Lake Pepin TMDL Modeling Study, upstream of Lock & Dam 1.

Contact: Norm Senjem, Minnesota Pollution Control Agency, 507-280-3592

Source and purpose: This modeling project is under consideration for 2008, but is still undefined.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: NA

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

Minnesota Pollution Control Agency (2006) Upper Mississippi River -- Lake Pepin Water Quality Modeling Project, Year 1 Report, 67p. http://www.pca.state.mn.us/publications/reports/lakepepin-year1report.pdf

Source and purpose: A progress report of the first year of the Lake Pepin Water Quality Modeling Project.

Summary of tools used to determine hydraulic mixing: This report describes progress during year 1 of the project, which will be completed in June, 2007. The model developed for this study will encompass the Upper Mississippi River from Lock and Dam No. 1 through the outlet of Lake Pepin. The models used are ECOMSED (hydrodynamic/sediment transport simulation model), and AESOP (water quality model).

Summary of results as they relate to hydraulic mixing and setting: NA: The project may produce findings about mixing in the upper Mississippi, but this year end report gives no insight into mixing processes.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: The project will produce important river information in the future, probably related to sedimentation and sediment transport.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

Payne, G. A. (1995) Ground-Water Baseflow to the Upper Mississippi River Upstream of the Minneapolis-St. Paul Area, Minnesota During July 1988. U. S. Geological Survey Open-File Report 94-478. http://pubs.er.usgs.gov/usgspubs/ofr/ofr94478

Source and purpose: USGS report estimating the groundwater interaction of the Mississippi River upstream of Minneapolis.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: This report presents the results of estimates of ground-water gains and losses in six subreaches of the Mississippi River from the headwaters reservoirs to Anoka, Minnesota during July 1988 and lists low-flow statistics for the Mississippi River near Anoka for 1933-1993 and Mississippi River at St. Paul, Minnesota for 1895, 1897, 1901-05, and 1907-93.

Applicability to Mississippi River: Moderate: Although this report doesn't include information about groundwater mixing with surface water, it does supply some site-specific groundwater discharge information.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Groundwater:* Groundwater is entering the Mississippi River and affecting the water composition.

Theoretical components: NA

Pujol, L. and Sanchez-Cabeza, J. A. (2000) Use of tritium to predict soluble pollutants transport in Ebro River waters (Spain). Environ. Pollut. 108(2), 257-269.

Source and purpose: This peer-reviewed journal article uses tritium as a radioactive tracer to determine the longitudinal dispersion coefficient and velocity of the Ebro River, Spain.

Summary of tools used to determine hydraulic mixing: The one-dimensional advection-diffusion equation was solved for the case of non-instantaneous tracer release (Tritium) on the Ebro River in Northeast Spain. The longitudinal dispersion coefficient and velocity were determined using three different approaches: analytical, box-type and numerical.

Summary of results as they relate to hydraulic mixing and setting: The results of this work can be used to predict the movement and dispersion of soluble pollutants in the Ebro River under constant discharge conditions.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate. While the results of this work can be used to predict the movement and dispersion of a soluble pollutant in a river system, the reach of the Ebro River evaluated has the following characteristics: river discharge ranges from 178 m3/s to 915 m3/s, longitudinal dispersion coefficient ranged from 5 +/- 31 to 392 +/- 45 m^2/s and mean velocities ranged from 0.558 +/- 0.011 to 1.278 +/- 0.019 m/s.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

Lock-and-dams: The study area is located downstream of two dams. The dams were used to create a constant flow rate (ranged from 178m^3/s to 915 m^3/s) so that the one-dimensional advection-diffusion equation could be solved.

Theoretical components: *Equations*

Putz, G. and Smith, D. W. (2001) Field measurement and modelling of two-dimensional river mixing. Water Sci. Technol. Water Supply 1(2), 57-65.

Source and purpose: This peer-reviewed journal article presents an overview of two-dimensional river mixing theory.

Summary of tools used to determine hydraulic mixing: Tracer methods for delineating effluent plumes resulting from continuous or transient input to rivers are described and the results of tracer studies conducted on the Athabasca River in Canada are presented. A comprehensive two-dimensional steady or unsteady input model (Advection Optimization Grid, AOG) is presented to predict the transverse mixing characteristics of the Athabasca River.

Summary of results as they relate to hydraulic mixing and setting: The results of this study can be used to accurately simulate the two-dimensional mixing of a tracer downstream of a steady state or slug injection into a river. Application of the AOG mixing model requires a significant number of cross-section surveys and flow characterization measurements.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High. The application of this mixing model should be suitable for any river system given the input data is available. This study concludes that the mixing model is accurate when compared to data collected on the Athabasca River which had the following characteristics at the time of the study: average discharge of 960 m^3/s (for the steady state injection test) and 876 m^3/s (for the slug test); average width of 302 m; average depth of 2.92 m; and an average velocity of 1.2 m.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

Tributaries: Downstream of a major tributary entering the river there is evidence of a dilution effect in the sample measurements. The effect continues for 13.5 km.

Theoretical components: *Equations, Transverse mixing coefficient*

Rathbun, R. E. and Rostad, C. E. (2004) Lateral mixing in the Mississippi River below the confluence with the Ohio River. Water Resources. Res. 40(5), [np].

Source and purpose: This peer-reviewed journal determined lateral dispersion factors and dispersion coefficients for three sections of the Mississippi River below its confluence with the Ohio River.

Summary of tools used to determine hydraulic mixing: Two dissolved constituents already present in the study area were used as dispersants: specific conductance and the industrial organic compound TTT (trimethyltriazinetrione). Lateral concentration distributions of the two dispersants were measured at four cross sections below the confluence. Three stream tube models were used to compute lateral diffusion factors from these data.

Summary of results as they relate to hydraulic mixing and setting: Results of this study provide lateral dispersion coefficients for a water discharge not previously reported in the literature as well as new values for the Mississippi River.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate. Resultant lateral dispersion coefficients are for water discharges not previously reported in the literature. The lateral diffusion factors may not be transferable to the reach of the Mississippi of interest because they were determined using cross sections below a major confluence, and because the mean water discharge measurements at the time of sampling were 29,500 m^3/s. With this in mind, the knowledge of the lateral mixing characteristics of rivers is necessary in estimating how dissolved constituents in a discharge to the river along the bank will disperse across the river below the outfall.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

River channel type/geometry: Lateral dispersion coefficients included values for a relatively straight section, a section with two sharp bends and several islands, and a section with four sharp bends, several smaller changes in flow direction, and several small islands.

River islands: See above description for river channel type

Theoretical components: *Equations, longitudinal dispersion coefficient, transverse dispersion coefficient*

Schoenberg, M. E. (1994) Characterization of Ground-Water Discharge from Bedrock Aquifers to the Mississippi and Minnesota Rivers at Three Areas, Minneapolis-St. Paul Area, Minnesota. U. S. Geological Survey Water-Resources Investigations Report 94-4163.

Source and purpose: A USGS report presenting the groundwater interaction with the Mississippi River in the Minneapolis-St. Paul area.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: Along the Mississippi River between Fridley and Brooklyn Center a buried valley underlying the river cuts through the overlying terrace deposits and glacial-drift deposits into the St. Peter aquifer and a rubble zone between the St. Peter and Prairie du Chien-Jordan aquifers. Shallow groundwater discharges to springs along the edge of the river.

About 5 miles upstream of the confluence of the Minnesota and Mississippi rivers lies a post-glacial valley cut through thin glacial drift in the St. Peter aquifer. Ground water flows to the Mississippi as no confining unit separates the St. Peter aquifer and the river. Although this report contains no information on mixing it does provide site-specific hydrogeologic x-sections and groundwater modeling.

Applicability to Mississippi River: High: This report provides a good overall groundwater characterization of the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

Seo, I. W. and Baek, K. O. (2004) Estimation of the Longitudinal Dispersion Coefficient Using the Velocity Profile in Natural Streams. J. Hydraul. Eng. 130(3), 227-236.

Source and purpose: A peer reviewed journal providing a new method of estimating the longitudinal dispersion coefficient.

Summary of tools used to determine hydraulic mixing: Transverse velocity distributions in natural streams are used to predict the longitudinal dispersion coefficient. This new method is compared to classic estimation of longitudinal dispersion coefficients completed by five others in the 1970s and 1990s.

Summary of results as they relate to hydraulic mixing and setting: The results show that the transverse velocity profile model and the prediction of the longitudinal dispersion coefficient based on that model are in good agreement with observed data.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: Provides a method to estimate the longitudinal dispersion coefficient.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: *Equations, Longitudinal dispersion*

Seo, I. W. and Cheong, T. S. (2001) Moment-Based Calculation of Parameters for the Storage Zone Model for River Dispersion. J. Hydraul. Eng. 127(6), 453-465.

Source and purpose: Peer reviewed journal providing a method for estimating parameters for the storage zone model for river dispersion.

Summary of tools used to determine hydraulic mixing: The storage zone model for river dispersion attempts to describe the skewness of concentration distribution observed in natural rivers.

Summary of results as they relate to hydraulic mixing and setting: This paper deals with estimation of parameters used in the storage zone model and concludes that the moment matching method is in good agreement with observed parameters and that the storage zone model could accurately describe dispersion in natural streams. The validation was completed in a lab under low flow conditions with pools and riffles.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: theoretical and lab-based; lab conditions did not simulate conditions likely to be observed in the Mississippi River. Provides a method to describe mixing in natural rivers.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: *Equations*

Seo, I. W. and Cheong, T. S. (1998) Predicting longitudinal dispersion coefficient in natural streams. J. Hydraul. Eng. 124(1), 25-32.

Source and purpose: Peer reviewed journal presents a method to estimate the longitudinal dispersion coefficient in natural streams.

Summary of tools used to determine hydraulic mixing: This paper compares previously derived equations for estimating the longitudinal dispersion coefficient with a new method.

Summary of results as they relate to hydraulic mixing and setting: The new method uses easily measured physical features (width, depth, shear velocity, and average cross-sectional velocity) to estimate the longitudinal dispersion coefficient.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: The longitudinal dispersion coefficient could be estimated from measurable characteristics instead of dye-tracer study.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Channel Geometry:* This method shows that for large rivers over 200 m wide that Liu and Fischer equations overestimate the longitudinal dispersion coefficient.

Theoretical components: *Equations, Longitudinal Dispersion*

Singh, S. K. and Beck, M. B. (2003) Dispersion Coefficient of Streams from Tracer Experiment Data. J. Environ. Eng. 129(6), 539-546.

Source and purpose: Peer reviewed journal presents a method for simultaneous estimation of dispersion coefficient, effective velocity, and effective injected mass of tracer, from a temporal concentration profile observed at a downstream section.

Summary of tools used to determine hydraulic mixing: This paper presents a new way to estimate the longitudinal dispersion coefficient of streams and also examines the ability of 6 previously derived methods for estimating coefficients.

Summary of results as they relate to hydraulic mixing and setting: The paper highlights the extreme differences in longitudinal dispersion coefficient among the available methods.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: This paper presents a method to estimate longitudinal dispersion, if a dye-tracer study is completed. It also presents a method of back-calculating the amount of chemicals released by industries or an accident.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Spills:* Presents a method to estimate the amount of injected chemicals.

Channel Geometry: A method of estimating stagnant zones in the a river reach is examined.

Theoretical components: *Equations, Longitudinal Dispersion*

Somlyody, L. (1977) Dispersion Measurement on the Danube. Water Research 11(4), 411-417.

Source and purpose: Peer reviewed journal discussing a dye-tracer study on the Danube.

Summary of tools used to determine hydraulic mixing: Three tracer experiments in a 52km reach of the Danube (studied flow = 1050-1900m^3/s, average width = 500m, average depth = 5m) conducted and transverse and longitudinal mixing were studied. A method is developed for determining the transverse dispersion coefficient from tracer measurements.

Summary of results as they relate to hydraulic mixing and setting: The dispersion coefficient was more than twice as high during high flows as during low flows.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: This stretch of the Danube is much larger than the MWMO reach of the Mississippi.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Flow Rate:* Longitudinal dispersion in the Danube increased with flow rate increases.

Theoretical components: *Longitudinal Dispersion coefficient, Transverse dispersion coefficient*

Stefan, H. G. and Johnson, T. R. (1987) Effluent Sampling Location and Duration Study For the Metropolitan Wastewater Treatment Plan, St. Paul, MN. Saint Anthony Falls Hydraulic Laboratory Project Report Number 259.

Source and purpose: Saint Anthony Falls Hydraulic Laboratory Project Report uses a model to determine sampling locations in a WWTP chlorination basin.

Summary of tools used to determine hydraulic mixing: A 1:12 scale model was used to determine sampling locations along the reach of the WWTP chlorination basin.

Summary of results as they relate to hydraulic mixing and setting: Trying to get a representative sample is difficult due to site sampling frequency, sample collection, devices, and sample handling. There are difficulties where concentration gradients exist in depth or width. A testing program is recommended over a mathematical prediction in sampling site selection.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: Provides general information on sampling locations as they relate to weirs. Provides the option of creating a physical model of the MWMO river reach.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Weirs*: Increased settling of solids upstream and the accumulation of oil and grease downstream.

Theoretical components: NA

Stefan, H., Riley, M., Farrell, G., Yuling, C. (1984) Nearfield Water Quality of the Metro WWTP Effluent Mixing Zone in the Mississippi River Under Summer Conditions. Saint Anthony Falls Hydraulic Laboratory Project Report Number 231.

Source and purpose: Saint Anthony Falls Hydraulic Laboratory Project Report further investigates the nearfield mixing of the Metro WWTP studied in St. Anthony Falls Hydraulic Laboratory Project No. 214. The report specifically investigates the plunging of the effluent across the river as an underflow.

Summary of tools used to determine hydraulic mixing: Sampling of temperature, TDS, and chloride downstream of the metro wastewater treatment plant, with samples taken at the surface and at different depths. Provides a means to estimate farfield lengths for vertically stratified conditions. Assumes summer flow with the wastewater treatment plume being denser than the river.

Summary of results as they relate to hydraulic mixing and setting: There are two different hydraulic mixing scenarios that take place in the summer (during plunging flow) and which scenario is occurring is based on the flow in the river. If the river is flowing at high flows (above 30,000 cfs), the river is vertically well mixed with horizontal turbulent diffusion. If the river flow is below 10,000 cfs then the effluent is horizontally stratified with vertical turbulent diffusion. Between these flows either condition could occur depending on the strength of the plunging.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High. This study was conducted in Pool 2 of the Mississippi River below the inflow from the Metro WWTP. It demonstrates the impact that flows can have on the nearfield mixing regime in a stretch of the river.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

Flow Rate: Dictates the type of mixing that occurs when a stratified effluent plume enters the river.

Dilution effects: Dilution is controlled by flow rate. At flows in excess of 30,000 cfs, the effluent is quickly diluted and remains close to the near bank as a vertically mixed transversely spreading plume. At lower flows the plume remains vertically stratified and horizontally well mixed.

Theoretical components: NA

Stefan, H (1982) Mixing of the Metro Wastewater Plant Effluent with the Mississippi River Below St. Paul. Saint Anthony Falls Hydraulic Laboratory Project Report Number 214.

Source and purpose: Saint Anthony Falls Hydraulic Laboratory Project Report to provide qualitative and quantitative information on the mixing between the Metro WWTP effluent and the Mississippi River under summer flow conditions.

Summary of tools used to determine hydraulic mixing: The theory portion examines different levels of modeling complexity possible in hydraulic mixing. They arrive at using a stream tube model for horizontal mixing zone as the most detailed model available without intense data collection needs. The vertical mixing zone model is of the same form as the stream tube model but with the axis in the vertical instead of the transverse. The field data collection involved samples taken at locations downstream of the wastewater discharge channel, and isotherms and isopleths were plotted.

Summary of results as they relate to hydraulic mixing and setting: The horizontal mixing zone model was not explicitly solved to describe the mixing zone because the transverse mixing coefficient could only be guessed without field data. The author estimates the value to be between 3 and possibly as high as 6 correlating to a downstream lateral mixing zone of between 5 and 10 miles. They recommend further study of buoyancy induced transverse mixing in the Mississippi. The vertical mixing was found to occur more slowly than anticipated because of the plunging of the wastewater stream as it enters the river. This plunging is due to water temperature and high dissolved solids. In the field study, temperature, chloride, and TDS were the most consistent tracers of the wastewater treatment plume. The spread of effluent across the river appears completed within 0.5 miles from the outlet.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High. This study was conducted in Pool 2 of the Mississippi River below the inflow from the Metro WWTP. It shows the importance of the impact of boat traffic on vertical mixing and the importance of vertical stratification due to temperature and dissolved solids. The assumptions valid in this river reach will generally hold in the MWMO reach of the river. Assumptions may be invalid on the downstream side of St. Anthony Falls or in other locations that don't maintain a navigation channel.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Flow rate*: At flows below 5,000 cfs barge traffic controlled the vertical mixing. Flows between 5,000 and 20,000 cfs and both barge traffic and river bed mixing controlled. Flows greater than 20,000 cfs are controlled by river bed mixing.

Wind: The author concluded that wind would contribute to mixing at flows less than 5000 cfs, but is negligible at higher flows.

Field conditions (temperature and dissolved solids): The temperature and increased dissolved solids of the effluent plume increases vertical stratification in the river. In this case, the colder water sunk to the bottom and was not present at the surface until further downstream.

Wing dams: Not explicitly investigated but the author offers that the alternating series of wingdams will have an impact on the transverse mixing coefficient.

WWTPs: The effect of a mass into the stream requires that the displacement effect be accounted for. In general, this means that as water flows in the other water is pushed away from the point source. Jet effects (nearfield flow): The outlet channel widens considerable at the confluence with the Mississippi reducing the jet effects to negligible levels.

Vessel Traffic: Vertical mixing of the stratified river is very effectively accomplished by barge traffic. Three passes of tug boats appears sufficient to vertically mix the river.

Theoretical components: *Equations*

Stefan, H. and Gulliver, J. S. (1978) Effluent mixing zone in a shallow river. Journal of the Environmental Engineering Division 104, 199-213.

Source and purpose: Peer reviewed journal discussing the mixing characteristics of heated water effluent discharged to the Mississippi River in Monticello, MN.

Summary of tools used to determine hydraulic mixing: Contains theory and case study of heated water effluent downstream of the Monticello Nuclear Power Plant. The maximum width, maximum length, and enclosed surface area of a mixing zone are determined as a function of dilution ratio, discharge to river flow ratio and weather parameters.

Summary of results as they relate to hydraulic mixing and setting: The results can be used to set the discharge rates and temperature of effluent from the power plant.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: Provides data specific to the Mississippi River and the mixing characteristics of water with different densities.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

Industrial outfalls: Presents a method to determine the site-specific mixing zone of an industrial outfall. This study shows that the lateral spread of effluent from the shore is slow unless the discharge has a large initial momentum.

Field Conditions (Temperature): Explains the mixing of heated effluent entering the river at ambient temperature.

Theoretical components: *Equations, Field tests*

Stefan, H, Lake, G. R., Nguyen, C. V. (1976) Mixing and Heat Transfer of Cooling Water Discharges from the Monticello Nuclear Power Generating Plant into the Mississippi River. Saint Anthony Falls Hydraulic Laboratory Project Report Number 158.

Source and purpose: Saint Anthony Falls Hydraulic Laboratory Project Report to predict the thermal plume characteristics downstream of the Monticello Nuclear Power Generating Plant.

Summary of tools used to determine hydraulic mixing: 32 field surveys of water temperature downstream from the Monticello Nuclear Power Generating Plant. A two-dimensional turbulent diffusion model was used for description of the main features. Dimensionless number analysis was conducted for all significant variables.

Summary of results as they relate to hydraulic mixing and setting: The thermal plume follows the right bank of the river for the first three miles. The lateral spread of warm water into the Mississippi River is very gradual. The flow of the cooling water entering the river ranges from 208 cfs to 650 cfs.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High. Located on the Mississippi River upstream of the MWMO area and provides information about a number of mixing characteristics.

Summary of how river characteristics are affecting hydraulic mixing and time of travel:

Ice flows and blockages: Ice cover eliminates surface currents in the river; the effluent flow can develop a surface spreading pattern near the outlet more easily.

Flow rate: Dictates the type of mixing that occurs when a stratified effluent plume enters the river.

Wind: No significant wind impacts could be detected.

Field conditions (temperature): Under low discharge rates a cold water wedge can form in the outlet channel. This indicates that the water is not vertically well-mixed due to temperature gradation. Enhanced lateral surface spreading caused b the buoyancy of the warm water effluent was apparent by tilted isotherms near the outlet.

Theoretical components: *Equations*

Swamee, P. K., Pathak, S. K., Sohrab, M. (2000) Empirical Relations for Longitudinal Dispersion in Streams. J. Environ. Eng. 126(11), 1056-1063.

Source and purpose: Peer reviewed journal presenting a new method to predict the time variation of stream pollution concentrations.

Summary of tools used to determine hydraulic mixing: A six parameter concentration equation for dispersion of conservative and nonconservative pollutants has been proposed. The resulting equation can be used to solve two types of pollutant problems: (1) solving for hydraulic parameters and the c-t curve at a distance for a known pollutant input, and (2) obtaining the pollutant input, its location, and time of introduction.

Summary of results as they relate to hydraulic mixing and setting: The equation appears fairly accurate for concentration prediction.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: Theoretical paper without field studies or river characteristic-specific results.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: *Equations, Longitudinal dispersion*

Taylor, K. R., James, R. W., Helinsky, B. M. (1985) Traveltime and dispersion in the Potomac River, Cumberland, Maryland, to Washington, D.C. U. S. Geological Survey Water-Supply Paper 2257. HYPERLINK "http://pubs.er.usgs.gov/usgspubs/wsp/wsp2257" http://pubs.er.usgs.gov/usgspubs/wsp/wsp2257

Source and purpose: A USGS report of a traveltime and dispersion study using rhodamine dye in the Potomac River between Cumberland, Maryland and Washington, D.C..

Summary of tools used to determine hydraulic mixing: A time of travel study conducted using rhodamine dye.

Summary of results as they relate to hydraulic mixing and setting: The average flow over the 5-day study was 3,900 ft^3/s. The reach between Shepardstown and Fort Fredrick contains two dams (dams no. 4 and 5) that significantly impede the movement of water, and the river shows distinctly different mixing characteristics in these reaches.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High: This reach of the Potomac River seems to have similar characteristics of the Mississippi river in the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Dams:* The effect of mixing at the dams was most pronounced at low river discharges, and less pronounced at high discharge.

Flow Rate: See above description under *Dams.*

Theoretical components: *Equations, Longitudinal dispersion coefficient*

Teichmann, L., Reuschenbach, P., Mueller, B., Horn, H. (2002) 2D simulation of transport and degradation in the River Rhine. Water Sci. Technol. 46(6-7), 99-104.

Source and purpose: A peer reviewed journal describing creation of a 2D model for the simulation of mass transport and degradation of substances in the River Rhine.

Summary of tools used to determine hydraulic mixing: A 2D model of mixing in the River Rhine (discharge 778-994 m^3/s) uses convective and dispersive terms in the flow direction and a segmented exchange coefficient to describe transverse mixing.

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: This model is generic enough that it may be used for other large rivers although changes would need to be made to make this model applicable to the Mississippi River reach of concern.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: No specific river characteristics are related to hydraulic mixing or time of travel.

Theoretical components: *Transverse dispersion coefficient, Longitudinal dispersion coefficient*

Thene, J. R., Wang, J. (2002) Empire Wastewater Treatment Plant and Outfall: Outfall Mixing Zone Analysis. Saint Anthony Falls Hydraulic Laboratory Project Report Number 457.

Source and purpose: Saint Anthony Falls Hydraulic Laboratory Project Report to provide information on the mixing of the effluent with the flow of the Mississippi River and to provide support for the siting and orientation of the outfall pipe.

Summary of tools used to determine hydraulic mixing: Cornel Mixing Zone Expert System (CORMIX) modeling software. Modeling assumptions relate specifically to injecting effluent to the Mississippi River at a constant flow.

Summary of results as they relate to hydraulic mixing and setting: The angle of injection can greatly affect the rate of nearfield mixing and this theory may be able to be extrapolated to cover stormwater outfalls and other inflows.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate. The CORMIX modeling assumptions are valid for the Mississippi River in the MWMO. This methodology can be used under all reasonably anticipated conditions within the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Wind*: Wind would contribute to mixing at flows less than 5000 cfs, but is negligible at higher flows.

Wastewater treatment plants: WWTPs mix water in river through jet effects and displacement effects. The effect of the additional wastewater input and the downstream wastewater plume composition is described.

Theoretical components: *Modeling*

Three Rivers Park District (2006) Coon Rapids Dam Operations & Maintenance Plan, 29p., draft

Source and purpose: The Coon Rapids Dam operation and maintenance plan.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: Contains the dam operations and maintenance plan, contact information. Pool elevation data and discharge charts are available by request. The pool elevation is lowered from 830.1 to 824.1 feet each fall, usually near the end of October, and returned to 830.1 in the middle of April.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

U.S. Army Corps of Engineers. (1997) Riverine Emergency Management Model (REMM): User Manual Version 3.0.

Source and purpose: U.S. Army Corps of Engineers manual for use of REMM.

Summary of tools used to determine hydraulic mixing: The model is a computer program and associated river, chemical, and geographic information data files which compute the time of travel, and optionally, the fate of chemical spill on a river system for various flow conditions. The program is designed to model highly soluble point source chemical spills when little data about the spill is available.

Summary of results as they relate to hydraulic mixing and setting: Results would be obtained from modeling the MWMO reach using this program.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: This model uses 1-dimensional modeling of spills, this is not a likely model to use to assist with a monitoring plan.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: *Modeling*

U.S. Army Corps of Engineers. (planned) Reservoir Operating Plan Evaluation (ROPE) Study for Mississippi Headwaters. http://www.mvp.usace.army.mil/fl_damage_reduct/default.asp?pageid=143

Contact: Steve Clark, U.S. Army Corps of Engineers, 651-290-5278

Source and purpose: U.S. Army Corps of Engineers study to evaluate alternative operating plans for the federal reservoirs in the Mississippi Headwaters to improve operation of the system as a whole.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: The reservoirs are Gull Lake (near Brainerd), Whitefish Lake, Sandy Lake, Pokegama Lake, Leech Lake, Lake Winnibigoshish, and Lake Bemidji. The alternatives will be evaluated with respect to tribal trust resources; flood damage reduction; fish and wildlife habitat enhancement, restoration, and preservation; recreation and tourism; water quality and water supply; erosion and sedimentation; hydropower; and navigation on the lakes and rivers.

A draft Environmental Impact Statement (EIS) and report (two separate but related documents) are expected to be released to the public in the summer of 2007. The report will be a summary of the EIS and will be tailored for the general public.

Applicability to Mississippi River: Low. Reservoirs are all located in Mississippi Headwaters, not big impact on water levels in MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

U.S. Army Corps of Engineers (2004a) Water Control Manual: Upper and Lower St. Anthony Falls Locks and Dams, Minneapolis, Minnesota. Appendix SAF of the Master Water Control Manual, 168p.

Source and purpose: A USACE water control manual.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: The entire manual is related to river conditions within

the MWMO.

Applicability to Mississippi River: High: Contains extensive information about the dam, including descriptions, photographs, operation plan, contact information, history, watershed characteristics, data collection networks, hydrologic forecasts, and effects of the water control plan.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

U.S. Army Corps of Engineers (2004b) Water Control Manual: Lock and Dam No. 1, Minneapolis, Minnesota. Appendix 1 of the Master Water Control Manual, 98p.

Source and purpose: A USACE water control manual.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: The entire manual is related to river conditions within the MWMO.

Applicability to Mississippi River: High: Contains extensive information about the dam, including descriptions, photographs, operation plan, contact information, history, watershed characteristics, data collection networks, hydrologic forecasts, and effects of the water control plan.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

U.S. Army Corps of Engineers (2003a) Water Control Manual: Lock and Dam No. 2, Hastings, Minnesota. Appendix 2 of the Master Water Control Manual, 164p.

Source and purpose: A USACE water control manual.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: The manual provides river conditions downstream of the MWMO.

Applicability to Mississippi River: Moderate: Contains extensive information about the dam, including descriptions, photographs, operation plan, contact information, history, watershed characteristics, data collection networks, hydrologic forecasts, and effects of the water control plan.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

U.S. Army Corps of Engineers (2003b) Water Control Manual: Lock and Dam No. 3, Red Wing, Minnesota. Appendix 3 of the Master Water Control Manual, 136p.

Source and purpose: A USACE water control manual.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: The manual provides river conditions far downstream of the MWMO.

Applicability to Mississippi River: Low: Contains extensive information about the dam, including descriptions, photographs, operation plan, contact information, history, watershed characteristics, data collection networks, hydrologic forecasts, and effects of the water control plan.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

U.S. Army Corps of Engineers (2002) Water Control Manual: Lock and Dam No. 4, Minneapolis, Minnesota. Appendix 4 of the Master Water Control Manual, 115p.

Source and purpose: A USACE water control manual.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: The manual provides river conditions far downstream of the MWMO.

Applicability to Mississippi River: Low: Contains extensive information about the dam, including descriptions, photographs, operation plan, contact information, history, watershed characteristics, data collection networks, hydrologic forecasts, and effects of the water control plan.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

U.S. Environment Protection Agency (2002) User's Manual for Environmental Fluid Dynamics Code.

Source and purpose: A user's manual for EFDC-Hydro.

Summary of tools used to determine hydraulic mixing: Blumberg-Mellor model, Lagrangian transport model

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High: This model may be a useful resource to help define mixing in the MWMO stretch of the Mississippi.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: Modeling

U.S. Environment Protection Agency (2006) Updated Model Report for Christina River Basin, Pennsylvania, Delaware, and Maryland, High-Flow Nutrient and DO TMDL Development.

Source and purpose: US EPA modeling report in support of a DO and nutrient TMDL.

Summary of tools used to determine hydraulic mixing: EFDC Model

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: The model used in this TMDL may be a useful resource to help define mixing in the MWMO stretch of the Mississippi.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: Modeling

Vandenberg, J. A., Ryan, M. C., Nuell, D. D., Chu, A. (2005) Field evaluation of mixing length and attenuation of nutrients and fecal coliform in a wastewater effluent plume. Environ. Monit. Assess. 107(1-3), 45-57.

Source and purpose: A peer reviewed journal that uses conductivity and chloride measurements to describe mixing rather than a dye-tracer study.

Summary of tools used to determine hydraulic mixing: Presents an alternative to dye tracer studies using conductivity and chloride measurements. The Bow River meanders through Calgary at approximately 1.5 m deep and 100 m wide and is situated in a largely undeveloped basin in the Rocky Mountains.

Summary of results as they relate to hydraulic mixing and setting: It was shown that mixing varied between seasons despite flow conditions, indicating that single dye tracer studies may be insufficient for modeling hydraulic systems. Complete vertical mixing can be expected within a distance of 20-100 times the river depth. Complete transverse mixing can be expected within a distance of 100-350 times the river width.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate: The Bow River is a fairly similar river to the Mississippi River in the MWMO. The main difference being that river upstream of Calgary is a largely undeveloped mountainous area. The information about seasonal variation and WWTPs should translate the Mississippi.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *WWTPs*: Uses conductivity and chloride to measure effluent mixing.

Seasonal variation: The WWTP plume exhibited much different nutrient attenuation characteristics in the month of April compared to the month of October presumably due to macrophyte uptake of nitrates in October.

Theoretical components: *Field Studies*

Voigt, R. L. and Kostic, S. (1998) Study of Plant Effluent Mixing & Outfall Location Selection for MCES South Washington County Wastewater Treatment Plant. Saint Anthony Falls Hydraulic Laboratory Project Report 418.

Source and purpose: Saint Anthony Falls Hydraulic Laboratory Project Report to investigate the effects of outfall location on effluent mixing.

Summary of tools used to determine hydraulic mixing: Cornel Mixing Zone Expert System (CORMIX) modeling software. Assumptions used in modeling relate specifically to injecting effluent to the Mississippi River at a constant flow.

Summary of results as they relate to hydraulic mixing and setting: The angle of injection can greatly affect the rate of nearfield mixing and this theory may be able to be extrapolated to cover stormwater outfalls and other inflows.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Moderate. The CORMIX modeling assumptions are valid for the Mississippi River in the MWMO. This methodology can be used under all reasonably anticipated conditions within the MWMO.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: *Wind*: The author concluded that wind would contribute to mixing at flows less than 5000 cfs, but is negligible at higher flows.

Wastewater treatment plants: WWTPs mix water in river through jet effects and displacement effects. The effect of the additional wastewater input and the downstream wastewater plume composition is described in this paper.

Vessel traffic: Vertical mixing of the stratified river is very effectively accomplished by barge traffic. Three passes of tug boats appears sufficient to vertically mix the river.

Theoretical components: *Modeling*

Winterstein, T. A. (1982) Annotated report and data inventory for the Mississippi and Minnesota Rivers, Minneapolis-St. Paul Metropolitan Area. U. S. Geological Survey Open-File Report 82-869, 99p. HYPERLINK "http://pubs.er.usgs.gov/usgspubs/ofr/ofr82869" http://pubs.er.usgs.gov/usgspubs/ofr/ofr82869

Source and purpose: A USGS annotated report and bibliography of the Mississippi and Minnesota Rivers in the Minneapolis-St. Paul area.

Summary of tools used to determine hydraulic mixing: NA

Summary of results as they relate to hydraulic mixing and setting: NA

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: High: This annotated bibliography contains references to much data relevant to the Mississippi River reach of concern. It includes a report summary, and keywords for each citation. This report is very comprehensive and would be useful for finding baseline and background information about specific areas within the MWMO. The major drawback of this report is that it is over 20 years out of date.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: NA

Theoretical components: NA

Yotsukura, N., Fischer, H. B., Sayre, W. W. (1970) Measurement of mixing characteristics of the Missouri River between Sioux City, Iowa, and Plattsmouth, Nebraska. U. S. Geological Survey Water-Supply Paper 1899-G. HYPERLINK "http://pubs.er.usgs.gov/usgspubs/wsp/wsp1899G" http://pubs.er.usgs.gov/usgspubs/wsp/wsp1899G

Source and purpose: USGS report on the mixing characteristics of the Missouri River.

Summary of tools used to determine hydraulic mixing: Longitudinal dispersion, transverse mixing, channel geometry, and transverse velocity distribution were made in the Missouri River at a flow of 33,000 cfs.

Summary of results as they relate to hydraulic mixing and setting: The longitudinal dispersion coefficient is one of the largest ever measured and indicated that values derived from small straight channels and laboratory experiments may underestimate the coefficient. Much work has been done on longitudinal dispersion in rivers since this work was completed.

Summary of river conditions within MWMO: NA

Applicability to Mississippi River: Low: This paper is largely out of date but does provide a test procedure for calculating the longitudinal and transverse mixing coefficients.

Summary of how river characteristics are affecting hydraulic mixing and time of travel: Specific river characteristics not discussed.

Theoretical components: *Longitudinal dispersion, Transverse mixing coefficient, Field tests*

Annotated Bibliography for Monitoring Protocols:

Bibliography contains complete citations for each document, plus the following information:

Source, type, and purpose: Name of sponsor, type of document, reason done.

Applicable river reach: Name and reach of river reported upon.

Applicable big river characteristics: Name of river characteristics from Table 1. Describe how river characteristic affects pollutant source, mixing, or time of travel, and the design of a monitoring protocol.

Summary of monitoring protocols: Name protocol developer, briefly describe protocol (i.e., variable, methodology, sampling frequency) and when possible, efficacy of protocol for this report. If none presented within report, then "Not applicable." If reference summarizes primary development of a protocol or scientific basis of protocol development, then so noted here.

Summary of river conditions within MWMO: Relevant results. If none presented within report, then "Not applicable."

Applicability of protocol to the MWMO: Similarities to and differences from the MWMO, conditions under which protocol can be used in the MWMO.

Overall relevance: Low, Moderate, or High. Assumptions or justification for assessment, based on 1) monitoring goals outlined in the MWMO's 2006 Watershed Management Plan, 2) importance of the upcoming Lake Pepin eutrophication TMDL allocation process, and 3) reported findings of the document.

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Andrews, W.J. (1996). Few volatile organic compounds detected in rivers and ground water in the Upper Mississippi River Basin, Minnesota and Wisconsin: U.S. Geological Survey Fact Sheet FS-095-96, 2 p. http://mn.usgs.gov/umis/bibl.dir/voc.fact.sheet.html

Source type and purpose: USGS NAWQA fact sheet assessing pollutant distribution

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable river characteristics: Atmospheric deposition and groundwater discharge, both contributing low concentrations of volatile organic compounds (VOCs) to river baseflow, therefore monitoring strategy should focus on baseflow grab sampling rather than intensive stormflow sampling.

Summary of monitoring protocols: USGS (and state and federal agencies that used similar sample collection and analytical methods), VOCs collected in manual grab samples.

Summary of river conditions within MWMO: From 1978-1994, VOCs were detected in less than five percent of water samples from rivers and wells. The most frequently detected VOCs were commonly used solvents and gasoline components.

Applicability of protocol to the MWMO: Protocol appropriate for monitoring VOCs within the MWMO. Due to their volatility, VOCs are more likely to be detected in ground water than in rivers.

Overall relevance: Low. Assuming MWMO will leave expense of VOC monitoring to regulatory agencies.

Andrews, W.J., Fallon, J.D., and Kroening, S.E. (1995). Water-quality assessment of the Upper Mississippi River Basin, Minnesota and Wisconsin--volatile organic compounds in surface and ground water, 1978-94: U.S. Geological Survey Water-Resources Investigations Report 95-4216 , 39 p.

Source, type, and purpose: USGS NAWQA report assessing pollutant distribution.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Atmospheric deposition and groundwater discharge, both contributing low concentrations of volatile organic compounds (VOCs) to river baseflow, therefore monitoring strategy should focus on baseflow grab sampling rather than intensive stormflow sampling.

Summary of monitoring protocols: USGS (and state and federal agencies which used similar sample collection and analytical methods), VOCs collected in manual grab samples.

Summary of river conditions within MWMO: VOCs were generally detected at similar frequencies, but at higher concentrations, in water samples from wells completed in sand and gravel aquifers than in water samples from wells completed in bedrock aquifers. Trichloroethene, a commonly-used degreasing agent in dry cleaning, metal cleaning, and cleaning septic lines, was the most frequently detected target VOC in ground water sampled from wells completed in both sand and gravel and bedrock aquifers. VOCs were most commonly detected in ground water in the vicinity of identifiable emission sites of VOCs, such as landfills, dumps, or major industries. The target VOCs were detected in less than five percent of ground-water samples at relatively low concentrations, generally near detection limits which ranged from 1 to 5 micrograms per liter.

Applicability of protocol to the MWMO: Due to their volatility, VOCs are more likely to be detected in ground water than in rivers. Protocol is appropriate for monitoring VOCs within the MWMO area, which includes both VOC sources and permeable aquifers.

Overall relevance: Low. Assuming MWMO will leave expense of VOC monitoring to regulatory agencies.

Andrews, W.J., Fallon, J.D., Kroening, S.E., Lee, K.E., and Stark, J.R. (1996). Water-Quality Assessment of Part of the Upper Mississippi River Basin, Minnesota and Wisconsin--Review of Selected Literature: U.S. Geological Survey Water-Resources Investigations Report 96-4149 , 21 p.

Source, type, and purpose: USGS NAWQA report to develop an understanding of water quality conditions within the Upper Mississippi study area.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Tributaries, groundwater, field conditions, and land use of contributing area. Land use patterns contribute to surface runoff and infiltration to groundwater, which influence water quality of streams and rivers.

Summary of monitoring protocols: A variety of protocols from USGS and others for surface water, groundwater, aquatic biology and ecology.

Summary of river conditions within MWMO: This report compiles selected sources of information that were used to aid in understanding water quality issues and processes that form the basis of the sampling design for the study.

Applicability of protocol to the MWMO: The MWMO area is included within the study area.

Overall relevance: Low. Comprehensive compilation of literature, but analysis of study results can be found elsewhere.

Angradi, T.R., Schweiger, E.W., Hill, B.H., Bolgrien, D.W., Lazorchak, J.M., Emery, E.B., Jicha, T.M., Thomas, J.A., Klemm, D.J., Peterson, S.A., Walters, D.M., Johnson, B.R., and Bagley, M. (2006). Environmental Monitoring and Assessment Program Great River Ecosystems (EMAP-GRE) field operations manual, U.S. Environmental Protection Agency, 227 pp. http://www.epa.gov/emap/greatriver/fom.html

Source, type, and purpose: U.S.EPA protocol for broad statistical assessments of large river ecosystems in the central basin of the U.S.

Applicable river reach: Major portions of the Missouri, Upper Mississippi, and Ohio Rivers, including that portion of the MWMO area below Lower St. Anthony Falls (LSAF).

Applicable big river characteristics: Substrate properties, riparian vegetation, and primary productivity. Plankton assemblages are important to the trophic structure of larger rivers. Plankton and periphyton (e.g., algae) respond rapidly to a number of anthropogenic disturbances. Riparian ecosystems contribute to and moderate the flux of materials and energy between terrestrial and aquatic habitats.

Summary of monitoring protocols: U.S.EPA protocol for July-September period sampling of main channel water chemistry and plankton, littoral fish and macroinvertebrates, and riparian vegetation. Seven sites located in the Mississippi reach between LSAF and Prescott were sampled in 2004 and 2005. Report is example of how to collect physical, chemical, and biological data with a single monitoring program. Good summary of quality assurance (QA) methods used throughout the many steps of such a program.

Summary of river conditions within MWMO: The results of sampling conducted in 2004 and 2005 have not yet been published.

Applicability of protocol to the MWMO: Sample design does not directly apply to the MWMO, in that the monitoring objective is to assess ecosystem health for broad areas (e.g., entire Upper Mississippi), but the monitoring techniques used for this program are fitting for the MWMO reach of the Mississippi.

Overall relevance: Moderate.

Ayers, M., R. Brown, and G. Oberts (1985). Runoff and chemical loading in small watersheds in the Twin Cities Metropolitan Area, Minnesota. U.S. Geological Survey Water-Resources Investigations Report 85-4122, U.S. Geological Survey, St. Paul, Minnesota.

Source, type, and purpose: USGS report to present interpretations and relationships derived from analyses of runoff and chemical loading, based on data reported by Payne et al. (1982).

Applicable river reach: Several rivers, streams, and storm sewers within the seven-county Twin Cities Metropolitan Area.

Applicable big river characteristics: Precipitation, elevation, storm outfalls, field conditions, suspended sediment, and nutrient loading and cycling. Rainfall rate and elevation gradient across a subwatershed are both key factors in the speed of storm runoff, especially in urban areas where runoff from impervious areas is routed via storm outfalls into a major river. The speedier the storm runoff, the more likely that that runoff will entrain sediments and chemical constituents on its way to the river. Monitoring strategies in each subwatershed should account for the anticipated speed of response to storm runoff, and treatment strategies should consider ways to slow the speed of response.

Summary of monitoring protocols: USGS protocols described in Payne et al. (1982) based on anticipated speed of hydrologic response, with stage recorders at most sites, and a combination of manual grab and automated sampling. Due to data availability, the different site types (see below) were analyzed with different regression methods, casting uncertainty on the differing results for each site type. Protocol was insufficient for one of the study objectives, which was to obtain reliable regression models as a method to estimate the storm and annual water quality loadings from unsampled subwatersheds.

Summary of river conditions within MWMO: This document provides regression models and an interpretation of the data for 17 sites that had continuous stage readings. The annual runoff for the three types of sites (six rural rivers, four urban rivers, and seven storm sewers) was 14-, 17-, and 27-percent of the annual rainfall, respectively. Results of this study suggest that as topographic relief and urbanization increase, so do runoff volume and the need for measures to control runoff. A strong dependence of loading on runoff volume suggested that measures to detain rainfall at or near where it

falls should reduce runoff volumes and most runoff loading.

Applicability of protocol to the MWMO: General protocol design of increased monitoring frequency for faster runoff response is valid. However, using inconsistent regression analysis method for different types of sites is problematic.

Overall relevance: Moderate. Assuming MWMO would like to monitor urban streams and storm runoff outfalls.

Brown, R.G. (1984). Atmospheric deposition of selected chemicals and their effect on nonpoint-source pollution in the Twin Cities Metropolitan Area, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 83-4195, 24 pp.

Source, type, and purpose: USGS report to interpret the contribution of atmospheric deposition to nonpoint source pollution.

Applicable river reach: One rural and three urban subwatersheds in the Twin Cities Metropolitan Area, including Shingle Creek located within the MWMO area.

Applicable big river characteristics: Precipitation, atmospheric deposition, and land use of contributing area. Seasonal rainfall patterns across the upper Midwest and localized land use patterns affect the atmospheric transport of land-based pollutants. Monitoring strategy should account for atmospheric transport of pollutants, and could even include atmospheric monitoring.

Summary of monitoring protocols: USGS protocol for the collection and analysis of dry and wet atmospheric deposition. Automated samplers occasionally malfunctioned, resulting in occasional collection of composite samples at two of four sites, rather than segregation of wet and dry atmospheric deposition.

Summary of river conditions within MWMO: Four subwatersheds were monitored for runoff and rainfall water quality, including nutrients, salts, and lead. About 20-percent of nitrogen and salt in atmospheric deposition occurred during wetfall, up to 40- to 50-percent in late spring, while about 95-percent of total phosphorus and lead deposition occurred during dryfall. The contributions of total atmospheric deposition to runoff load was lowest in those subwatersheds that had 3- to 4-percent open-water plus impervious area, as compared to others that had approximately 8-percent (Shingle Creek and Purgatory Creek). The average runoff load in these two creeks contributed from atmospheric deposition was 75-, 19-, and 50-percent for nitrite+nitrate-nitrogen, total phosphorus, and total lead, respectively. Shingle Creek subwatershed, containing more commercial industrial lands than the other subwatersheds, had the highest atmospheric and runoff loading rates for all variables.

Applicability of protocol to the MWMO: While the MWMO may not want to engage in monitoring for atmospheric deposition, any monitoring of surface water for nutrients should consider atmospheric deposition as a significant source of loading within the MWMO area. After this report was published, a federal ban on leaded gasoline greatly reduced the prevalence of lead in atmospheric deposition.

Overall relevance: High. Shingle Creek should be a key monitoring site for the MWMO.

Capel, P.D., Lin, M., and Wotzka, P.J. (1998). Wet atmospheric deposition of pesticides in Minnesota, 1989-94: U.S. Geological Survey Water-Resources Investigations Report 97-4026, 42 p.
http://mn.usgs.gov/pubs/atmospheric/atmospheric.html

Source, type, and purpose: USGS report to examine pesticides in rain throughout the state.

Applicable river reach: Atmospheric monitoring sites at twelve locations across Minnesota.

Applicable big river characteristics: Atmospheric deposition and groundwater discharge, both contributing low concentrations of pesticides to river baseflow, therefore monitoring strategy should focus on baseflow grab sampling rather than intensive stormflow sampling.

Summary of monitoring protocols: USGS collection of integrated week-long precipitation samples for pesticide analyses. The precipitation collector was modified for this study with Teflon and glass to minimize the potential for sorption and contamination of pesticides by the plastic container. After an initial 15-month sampling period, sampling was limited to wet season (April-October).

Summary of river conditions within MWMO: The presence of agricultural pesticides (not registered for home and garden use) in rain and storm runoff in an urban area indicates their atmospheric transport from areas of agricultural use. The data indicate that flux into the watersheds from the rain is generally much greater than the flux out of the watersheds in the streams. Therefore, a large fraction of the pesticides deposited in rain is retained within the watersheds. For the urban area, this is on the order of 98 percent for the four most commonly observed herbicides in rain and runoff.

Applicability of protocol to the MWMO: Monitoring within the MWMO area should take into account atmospheric transport of pollutants from land uses outside of the MWMO area.

Overall relevance: Moderate. According to MDA (2006), Bassett Creek and Minnehaha Creek will be monitored for common urban pesticides. These data should be evaluated to assess whether the MWMO should monitor for pesticides.

Chick, J. H., B. S. Ickes, M. A. Pegg, V. A. Barko, R. A. Hrabik, and D. P. Herzog. 2005. Spatial structure and temporal variation of fish communities in the Upper Mississippi River System. U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin, May 2005. LTRMP Technical Report 2005-T004. 15 pp.

Source, type, and purpose: USGS report analyzing nine years of fish sampling data.

Applicable river reach: Five reaches of the Upper Mississippi River (above the Ohio River) and one reach on the Illinois River.

Applicable big river characteristics: Channel type, field conditions, substrate properties, and riparian vegetation, are all key factors in the quality and diversity of fish habitat. Monitoring strategy should account for a variety of fish habitats.

Summary of monitoring protocols: USGS electrofishing using a stratified random design to sample different fish habitats of a large river system.

Summary of river conditions within MWMO: Study indicated both large-scale and fine-scale patterns of number and composition of fish species.

Applicability of protocol to the MWMO: The MWMO is just upstream of one of the study reaches, Pool 4, and although there is little backwater or impoundments within the MWMO stretch of the Mississippi, this protocol is very appropriate if the MWMO should choose to sample fish.

Overall relevance: Moderate. Assuming MWMO is not planning to sample fish.

Edwards, T.K. and Glysson, G.D. (1999). Field methods for measurement of fluvial sediment. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, chap. A2. http://pubs.usgs.gov/twri/twri3-c2/

Source, type, and purpose: USGS monitoring protocol for collection and measurement of fluvial sediments.

Applicable river reach: All streams and rivers of the U.S.

Applicable big river characteristics: Flow rate, substrate properties, suspended sediment. Streamflow transports as much sediment as the energy of the stream will allow, maintaining the finer particles in suspension with turbulent currents and rolling or skipping the coarser particles along the streambed. Monitoring protocol needs to account for transport speed of different particle sizes.

Summary of monitoring protocols: USGS fluvial sediments protocol, which describes the design criteria and common types of sediment samplers for suspended load, bed load, and bed sediments. The sediment-sampling method and frequency of collection are dictated by the hydrologic and sediment characteristics of the stream, and sampling should place an emphasis on the collection of a statistically representative population of the sediment particles in transit.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: While sediment sampling technologies may have changed in a decade, the sediment sampling techniques described in this reference are still part of the federal "gold standard".

Overall relevance: High. Accurate sediment assessments will be important for the Lake Pepin eutrophication TMDL allocation process.

Engstrom, D.R. and Almendinger, J.E. (1998). Historical changes in sediment and phosphorus loading to the Upper Mississippi River: Mass-balance reconstructions from the sediments of Lake Pepin. Science Museum of Minnesota, St. Croix Watershed Research Station, Marine on St. Croix, MN. 48 pp.

Source, type, and purpose: Metropolitan Council Environmental Services report prepared by staff at the St. Croix Watershed Research Station to quantify human alteration of historical phosphorus and sediment loads to Lake Pepin.

Applicable river reach: Lake Pepin, a riverine lake within the Mississippi River.

Applicable big river characteristics: Tributaries, suspended sediment, nutrient cycling, and land use of contributing area. Lake Pepin serves as a settling basin for three large rivers that each flow from agricultural and/or forest lands through a major urban area. Monitoring strategy in this situation should include some measure of source apportionment.

Summary of monitoring protocols: Academically-proven (peer-reviewed and replicated) protocols for lake sediment coring, seismic survey, magnetic susceptibility, radioactive dating, grain-size analysis, trace metal sediment source signatures, phosphorus content and diatom identification.

Summary of river conditions within MWMO: The Minnesota River contributes 90-percent of modern sediment load to Lake Pepin, which is in-filling at 10-times natural background rates. Phosphorus concentrations in the lake are 4-times greater than background levels.

Applicability of protocol to the MWMO: These protocols apply to riverine lake sediments and could be applied to selected locations within the pools of the Mississippi River. Already, the National Park Service is planning to collect Mississippi River sediment cores for diatom analysis from 3-4 locations in the Twin Cities Metropolitan Area.

Overall relevance: High. This was the first comprehensive study quantifying the degradation of Lake Pepin and identifying potential pollutant source areas (which includes the MWMO area), ultimately leading to the Lake Pepin TMDL for eutrophication.

Fallon, J.D. (2000). Pesticides in streams in part of the Upper Mississippi River Basin, Minnesota and Wisconsin, 1974-94: U.S. Geological Survey Fact Sheet 066-00, 4 p.
http://mn.usgs.gov/publicationIndex.html#m

Source, type, and purpose: USGS fact sheet assessing pollutant distribution, follow-up to Fallon and others (1997).

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Land use of contributing area, pollutant fate, and substrate properties. Pesticide detection frequencies are a function of pesticide type (some of which persist longer in surface water than other types), land use (agricultural and/or urban), and timing of applications (seasonal vs. year-round).

Summary of monitoring protocols: USGS NAWQA sampling of pesticides in surface waters, plus data from six other monitoring agencies.

Summary of river conditions within MWMO: Fallon evaluated pesticide use data and water quality detections at 39 stream sites in forested, agricultural, and urban watersheds. Pesticides restricted for agricultural use were detected in urban streams, presumably delivered by atmospheric deposition. Herbicides were detected most frequently in agricultural stream water; whereas, organochlorine insecticides were detected most frequently in urban streambed sediment. The four most frequently detected herbicides typically were applied to the soil surface, rather than incorporated below the surface, making them vulnerable to surface runoff and wind erosion. Most measured concentrations were below levels considered harmful to human and aquatic health.

Applicability of protocol to the MWMO: Both urban and agricultural pesticides have been detected in urban streams.

Overall relevance: Moderate. According to MDA (2006), Bassett Creek and Minnehaha Creek will be monitored for common urban pesticides. These data should be evaluated to assess whether the MWMO should monitor for pesticides.

Fallon, J.D., and Chaplin, Brian (2001). Chloride-related studies in streams and ground water of the Twin Cities metropolitan area, Minnesota, 1996-98--A summary of published and new results [abs.]: Chloride Impacts to Local Waters, January 10, 2001, St. Paul, Minn. http://mn.usgs.gov/publicationIndex.html#m

Source, type, and purpose: USGS presentation abstract to evaluate de-icers salts in urban runoff, dominantly in located in northern states, as part of the nation-wide NAWQA results.

Applicable river reach: Streams in the Twin Cities Metropolitan Area, within a portion of the Upper Mississippi River basin.

Applicable big river characteristics: Land use of contributing area, and seasonal extremes. Urban lands overlying permeable sand and gravel are more vulnerable to infiltration of chloride-rich runoff of de-icers and therefore recharge streams during low streamflow conditions with chloride-rich waters. Choice of monitoring strategy (baseflow vs. stormflow) should take into account the permeability of surficial geology in urban areas.

Summary of monitoring protocols: USGS collection and interpretation of chloride concentrations, specific conductance, and streamflow.

Summary of river conditions within MWMO: Chloride concentrations correlated positively with percent impervious area (Pearson's coefficient r= 0.88), indicating that runoff of road de-icers may be a primary source of chloride. Chloride and percent impervious area correlated negatively with mayfly abundance and fish species richness and diversity. Shingle Creek, located within the MWMO area, was monitored continuously for two years and the results suggest that chloride-rich ground water recharges Shingle Creek from the overlying permeable sand and gravel during low streamflow conditions.

Applicability of protocol to the MWMO: In areas of permeable surficial geology, the application of de-icers to impervious areas can be expected to affect stream and river water quality during low flow and baseflow conditions, rather than snowmelt and storm runoff periods.

Overall relevance: Moderate. The MWMO is responsible for urbanized areas that overlie permeable geology.

Fallon, J.D. and McNellis, R.P. (2000). Nutrients and suspended sediment in snowmelt runoff from part of the Upper Mississippi River Basin, Minnesota and Wisconsin, 1997: U.S. Geological Survey Water-Resources Investigations Report 00-4165, 23 p. http://mn.usgs.gov/publicationIndex.html#m

Source, type, and purpose: USGS report to characterize the proportion of annual nutrient and suspended-sediment concentrations, yields, and loads that occur during the snowmelt period.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Seasonal extremes and land use of contributing area. Peak flows during snowmelt period carry higher concentrations of sediments and nutrients, with proportions of annual loading depending upon land use of contributing areas. Agricultural lands exposed by fall tillage contribute greater sediment runoff in snowmelt than urban lands with more impervious surfaces.

Summary of monitoring protocols: USGS NAWQA sampling for sediments, nutrients, and field water quality variables. Annual loads were calculated using the ESTIMATOR program.

Summary of river conditions within MWMO: Snowmelt runoff was sampled from 42 stream and river sites during March and April 1997, including some flood conditions. Forested and urban areas contributed low concentrations of particulate nutrients, while agricultural lands contributed high concentrations of dissolved nutrients. Snowmelt accounted for the largest proportion of annual loads from agricultural lands, a little less from forested lands, and least from urban lands.

Applicability of protocol to the MWMO: The snowmelt period should be considered in strategies aimed at monitoring and reducing loads of these constituents to streams. However, in predominantly urban areas, nutrient and sediment loads are more evenly distributed across the year. Snowmelt monitoring should not be ignored, but should be included in a program of year-round monitoring.

Overall relevance: High. Indicates that year-round sampling is important.

Flotemersch, J. E., Stribling, J. B., and Paul, M. J. (2006). Concepts and approaches for the bioassessment of non-wadeable streams and rivers. EPA 600-R-06-127. U.S. Environmental Protection Agency, Cincinnati, Ohio. 245 pp. http://www.epa.gov/eerd/rivers/index.html

Source, type, and purpose: U.S. EPA report, answering the mandate to develop standardized protocols for the bioassessment of large (i.e., nonwadeable) streams and rivers.

Applicable river reach: All non-wadeable streams and rivers within the U.S.

Applicable big river characteristics: Substrate type, and nutrient cycling. Aquatic biotas depend upon a healthy habitat in order to survive and flourish; this includes high water clarity, a moderate source of nutrients, and suitable substrate. Habitat assessment requires monitoring for a greater variety of variables than just collecting a water sample.

Summary of monitoring protocols: U.S. EPA developed this protocol for biological water quality variables, which are often considered to be efficient integrators of physical and chemical water quality conditions. The authors systematically compared alternative approaches and documented their performance characteristics, collaborating extensively with regional, State and Tribal scientists to ensure that the protocols were both technically feasible and economically practical. In particular, this report focuses on monitoring protocols for algae, benthic macroinvertebrates, and fish.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: This protocol is very applicable to the assessment of biological water quality conditions within the MWMO's area of the Mississippi River.

Overall relevance: High. Assuming that the MWMO is interested in these variables.

Fong, A.L. (2000). Water-quality assessment of part of the Upper Mississippi River Basin, Minnesota and Wisconsin--Ground-water quality in three different land-use areas, 1996-98: U.S. Geological Survey Water-Resources Investigations Report 00-4131, 37 p.
http://mn.usgs.gov/publicationIndex.html#m

Source, type, and purpose: USGS report to describe the current groundwater quality within the Upper Mississippi basin and assess the affect of three land uses on groundwater quality.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Groundwater discharge, fate and properties of pollutants, and land use of contributing area. Pollutants representing different land uses are differentially transported through groundwater systems and discharged to major rivers. The quality of groundwater discharge to the river is influenced by the land use of the contributing area and the aquifer materials. Monitoring strategy should consider land use indicators.

Summary of monitoring protocols: USGS protocols for sampling from groundwater wells and water quality analyses for over 200 variables.

Summary of river conditions within MWMO: Fong notes that land use and land cover are important factors affecting groundwater quality, especially in surficial sand and gravel aquifers. The quality of shallow surficial groundwater (water level less than 20 feet below ground) was compared in three different land-use areas: an urban residential and commercial area on the edge of the Anoka Sand Plain (urban study), an intensive agricultural area in the Anoka Sand Plain (agricultural study), and a forested area in the Bemidji-Bagley Sand Plain (forested study). In all three of the land-use areas under study, groundwater discharges to the Mississippi River. The groundwater in the urban area had higher conductance (salts) and VOCs, and lower dissolved oxygen, while that in the agricultural area had higher nitrate-nitrogen and pesticide detections. Groundwater in the forested area had the lowest concentrations for all variables.

Applicability of protocol to the MWMO: Some of the urban groundwater samples were collected within the boundaries of the MWMO area, and all of the aquifers studied discharged to the Mississippi River above the MWMO area. Protocol is applicable only if the MWMO plans to monitor groundwater quality.

Overall relevance: Low. Assuming the MWMO does not plan to monitor groundwater resources. However, it is important to monitor for water quality variables that are indicators of the land uses within the MWMO area, plus those upstream of the MWMO area.

Gilliom, R.J., Alley, W.M., and Gurtz, M.E. (1995). Design of the National Water-Quality Assessment Program: Occurrence and distribution of water-quality conditions. United States Geological Survey Circular 1112. http://water.usgs.gov/pubs/circ/circ1112.

Source, type, and purpose: USGS report on design of national monitoring program.

Applicable river reach: The rivers and streams of the U.S.

Applicable big river characteristics: Tributaries, groundwater discharge, and land use of contributing area. Speedy surface runoff from subwatersheds and baseline groundwater discharge can both be important contributors to the water quality and aquatic health of a river. Monitoring strategy needs to account for both the water quality variables and sampling frequency that represent the hydrology and land use of the contributing area.

Summary of monitoring protocols: This USGS national study design for surface water focuses on water-quality conditions in streams, using the following interrelated components: water-column studies, bed sediment and fish tissue studies, and ecological studies. Sampling designs for all three components rely on coordinated sampling of varying intensity and scope at "Integrator Sites," which are chosen to represent water-quality conditions of streams with large basins that are often affected by complex combinations of land-use settings, and at "Indicator Sites," which are chosen to represent water-quality conditions of streams associated with specific individual environmental settings. In selected locations, ground-water studies are co-designed with streamwater quality studies to investigate interactions between ground and surface waters. This reference discusses aspects of the scientific basis of protocol development.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: The USGS method of site selection, targeted for locations of expected pollutants, is appropriate for the small and highly-urbanized MWMO area.

Overall relevance: High. Assuming the MWMO is interested in targeting potential sources of pollution.

Goldstein, R.M., Lee, K., Talmadge, P., Stauffer, J.C., and Anderson, J.P. (1999). Relation of fish community composition to environmental factors and land use in part of the Upper Mississippi River Basin, 1995-97: U.S. Geological Survey Water-Resources Investigations Report 99-4034, 32 p.

Source, type, and purpose: USGS report to relate the composition of fish communities within the upper Mississippi River to environmental factors.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Channel type, substrate properties, field conditions, nutrient cycling, riparian vegetation, lock-and-dams. All of these factors influence the aquatic health and fish habitat of a large river like the Mississippi.

Summary of monitoring protocols: USGS fish sampling protocol. Data analysis was stratified by surficial geology and land use, and compared longitudinal fish distributions with corresponding human population density of contributing areas.

Summary of river conditions within MWMO: There is a discernible shift in the composition of fish communities from upstream to downstream of the metropolitan area, which goes beyond the zoogeographic limitation of the lock-and-dams. The pools in the Mississippi River decrease water velocities, allowing suspended sediment to sink and water temperatures to increase. Downstream of nutrient inputs from the agricultural Minnesota River, the warmer temperatures promote the growth of phytoplankton and increasing numbers of planktivores. The fish composition shifts from cool-water lotic species to warm-water lentic species.

Applicability of protocol to the MWMO: Protocol is applicable if the MWMO wants to collect fish samples.

Overall relevance: Moderate. Assuming that MWMO does not plan to sample fish, but that MWMO is interested in the aquatic health of this section of the Mississippi River.

Hanson, P.E. (1998). Pesticides and nitrates in surficial sand and gravel aquifers as related to modeled contamination susceptibility in part of the Upper Mississippi River Basin: U.S. Geological Survey Fact Sheet 107-98, 4p
http://mn.usgs.gov/pubs/contam_fs/contam_text.htm

Source, type, and purpose: USGS fact sheet to assess the distribution of groundwater contamination by pesticides and nitrates.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Groundwater discharge, nutrient cycling, and land use of contributing area. Pollutants representing different land uses are differentially transported through groundwater systems and discharged to major rivers. Monitoring strategy should consider land use indicators.

Summary of monitoring protocols: The occurrence of pesticides and nitrate (nitrite plus nitrate as nitrogen) in surficial sand and gravel aquifers in parts of Minnesota and Wisconsin was summarized as part of an analysis of historical water-quality data collected by State and federal monitoring agencies. Pollutant detections were compared to maps of land-use and maps of modeled groundwater susceptibility.

Summary of river conditions within MWMO: Groundwater samples with detection of pesticides and nitrate exceedances were located in areas of highly-susceptible groundwater. In addition, highly-susceptible groundwater located in agricultural areas had the highest concentrations of pesticides and nitrates. Although geologic and hydrologic conditions influence the water quality of surficial aquifers, contamination from pesticides and nitrates in the highest susceptibility areas appear to be associated with human activities.

Applicability of protocol to the MWMO: The MWMO area is primarily urban, not agricultural. However, this report confirms that land use has a strong influence on water quality.

Overall relevance: Moderate. Assuming that the MWMO does not plan to monitor groundwater quality but that groundwater discharge to the river is an important issue.

Holland, L. (1986). Effects of barge traffic on the distribution and survival of ichthyoplankton and small fishes in the Upper Mississippi River. Transactions of the American Fisheries Society 115: 162-165.

Source, type, and purpose: Academic journal article to assess the direct impacts of commercial vessel passage.

Applicable river reach: Above and below Pool 7 in the Upper Mississippi River, near

La Crosse, Wisconsin.

Applicable big river characteristics: Channel type, substrate properties, and vessel traffic. The turbulence of vessel traffic through navigation pools degrades the habitat of egg, larval, and adult stages of aquatic organisms. Monitoring strategy must account for water uses of all aquatic habitat settings.

Summary of monitoring protocols: Academically-proven (peer-reviewed and replicated) protocols for monitoring mortality and changes in distribution, from samples taken before and up to 90 minutes after vessel passage. Authors suggest another method is needed to evaluate impacts of barge passage because more than 200 vessel passages would need to be monitored to obtain minimally acceptable levels of accuracy and precision.

Summary of river conditions within MWMO: Barge traffic caused significant short-term changes in distribution of eggs and larvae. Mean catch of ichthyoplankton was reduced after passage of loaded downstream vessels. Mean catch in surface waters increased immediately after upstream passage of unloaded vessel. No consistent effect on catch of age-0 or small adults was evident. There was significant physical damage to eggs, but not to larvae or small fish.

Applicability of protocol to the MWMO: The portion of the Mississippi River within MWMO area experiences barge traffic. Sampling protocol could provide a snap-shot of the affect of vessels on aquatic organisms.

Overall relevance: Moderate. Protocol needs to be re-designed for greater accuracy.

James, W.F. (2006). Nutrient dynamics and budgetary analysis of the Lower Minnesota River: Interim Report 2006. U.S. Army Engineer Research and Development Center, Spring Valley, Wisconsin, 57 pp. http://www.metrocouncil.org/Environment/Water/LMRM/ documents/nutrient_interim.pdf

Source, type, and purpose: U.S. Army interim report to the Metropolitan Council Environmental Services to assess phosphorus availability and cycling in the Lower Minnesota River and downstream.

Applicable river reach: Lower Minnesota River, between Jordan, Minnesota and the confluence with the Mississippi River.

Applicable big river characteristics: Substrate properties, suspended sediment, and nutrient cycling. Phosphorus is a plant nutrient that tends to adsorb to sediment particles, therefore sediment dynamics within a large river influences phosphorus transport within and through the river reach. Monitoring strategies targeted at phosphorus budgets need to account for sediment transport of phosphorus.

Summary of monitoring protocols: U.S. Army Corps of Engineers collection of water samples and bed sediment cores for analysis of phosphorus components. Although phosphorus was equally in soluble and particulate forms, up to 75 % of the total P load was in a form that was biologically available for uptake. A significant portion of the TSS and particulate P load can be deposited in the river for later recycling.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: The land use and surficial geology above the MWMO area differs significantly from this study. However, the issue of nutrient cycling within a large river system is relevant to the MWMO.

Overall relevance: Moderate. Assuming the MWMO does not plan to undertake such intensive analysis of Mississippi River bed sediments.

Johnson, M.R. and Zelt, R.B (2005). Protocols for mapping and characterizing land use/land cover in riparian zones. U.S. Geological Survey Open File Report 2005-1302, 16 p.

Source, type, and purpose: USGS protocol developed for use by the NAWQA program to compare gaps in woodland distribution with nutrient enrichment in streams.

Applicable river reach: All streams and rivers within the U.S.

Applicable big river characteristics: Nutrient cycling, riparian vegetation, and primary productivity. Riparian zones influence the level of nutrient enrichment of stream ecosystems by: 1) filtering or uptake of nutrients, sediments, and some organic chemicals, 2) providing shade, moderating water temperatures and decreasing primary production, 3) stabilizing banks, and 4) providing habitat cover.

Summary of monitoring protocols: USGS protocol for mapping and characterizing riparian zones at both the segment and reach scales, using GIS-analysis of digital orthophoto quarter-quadrangles (DOQQs). Protocol includes step-by-step examples.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: This protocol would be a good starting point for riparian cover assessment by the MWMO; follow-up should include GPS ground-truthing.

Overall relevance: Moderate. Assessments of riparian zone cover should include field assessment of the accuracy of the GIS analysis, lacking in this protocol.

Kloiber, S. (2004). Regional progress in water quality: analysis of water quality data from 1976-2002 for the major rivers in the Twin Cities. Regional Report Number 32-04-045, Metropolitan Council Environmental Services, St. Paul, Minnesota.
http://www.metrocouncil.org/resources/resources.htm

Source, type, and purpose: Metropolitan Council Environmental Services report to evaluate the status and trends (1976-2002) of water quality in the three large rivers that pass through the Twin Cities Metropolitan Area (TCMA).

Applicable river reach: Water entering the TCMA (in the Mississippi River at Anoka, the Minnesota River at Jordan, and the St. Croix River at Stillwater) and water leaving the TCMA (in the Mississippi River at Red Wing).

Applicable big river characteristics: Tributaries, land use of contributing area, lock-and-dams, and WWTF. The water quality of the rivers as they flow through the lock-and-dam system of the metropolitan area is influenced by the land use of their contributing areas, and by the inputs from the metro WWTF. Monitoring strategy needs to account for expected inputs.

Summary of monitoring protocols: MCES protocol for biweekly sample collection from large rivers and EPA, ASTM, or APHA protocols for laboratory analyses.

Summary of river conditions within MWMO: This report found that the largest trends in these rivers have occurred for NH4, BOD5, and fecal coliform bacteria, decreasing at rates of 3-5% per year. These trends are probably due, in large part, to improvements in point source controls that occurred over the period from 1976 to 2002.

Applicability of protocol to the MWMO: The study area includes the portion of the Mississippi River that lies within the MWMO area. The monitoring design strategy, of monitoring large river inputs and outputs from an area, can be applied to the MWMO area.

Overall relevance: High. The nutrient, sediment, and biological variables monitored for this study are very relevant to the Lake Pepin TMDL, and it will be important for the MWMO to track the status and trends of these variables.

Kloiber, S. (2003). Aquatic resource assessment for the Twin Cities Metropolitan Area natural resources inventory and assessment. Regional Report Number 32-03-015, Metropolitan Council Environmental Services, St. Paul, Minnesota.
http://www.metrocouncil.org/resources/resources.htm

Source, type, and purpose: Metropolitan Council Environmental Services report prepared as part of an inventory and assessment of natural resources for the Twin Cities Metropolitan Area (TCMA).

Applicable river reach: All surface water resources within the TCMA, including 1,942 lakes (> 3 acres) and 5,479 km of streams and rivers.

Applicable big river characteristics: Channel type, riparian vegetation, water appropriations, and land use of contributing area. The quality of a resource for its users depends upon the quality of its habitat and health safety.

Summary of monitoring protocols: A GIS-based assessment process was used to compile selected physical, biological, and cultural indicators for surface water resources in the TCMA, which were evaluated to assign relative rankings of the resource value of the region's lakes and streams with regard to water supply, recreational, and ecological uses. A few data shortcomings were discussed as the source of uncertainties in the assessment process.

Summary of river conditions within MWMO: The Mississippi River above Fridley (upstream of the MWMO area) is rated of primary importance for regional water supply. The entire Mississippi River within the TCMA is ranked as having outstanding importance for regional recreational and ecological uses. The watershed condition of the MWMO area is rated as impacted or degraded.

Applicability of protocol to the MWMO: The study area includes the portion of the Mississippi River and contributing streams that lie within the MWMO area, therefore the MWMO probably does not need to repeat the analysis for some time.

Overall relevance: Moderate. This study uses an alternative method to evaluate water quality issues within the MWMO.

Kroening, S.E. (1998). Nutrient sources within the Upper Mississippi River Basin, Minnesota and Wisconsin, 1991-93: U.S. Geological Survey Fact Sheet 121-98, 4p.
http://mn.usgs.gov/pubs/sources/text.htm

Source, type, and purpose: USGS fact sheet to determine the relative importance of nutrient source types within the four major sub-basins of the Upper Mississippi River Basin.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Tributaries, land use of contributing area, and nutrient cycling. Elevated concentrations of nutrients in slower-moving reaches of streams and in lakes can result in eutrophication, which can ultimately result in fish kills. Excessive applications of nutrients to the land surface also could result in the leaching of more soluble forms, such as nitrate and ammonium.

Monitoring strategy should include all forms of nutrient loading.

Summary of monitoring protocols: The amount of nutrients contained in fertilizer, livestock manure, municipal wastewater, atmospheric deposition, and legume residues were quantified in each of the four major drainage basins within the Upper Mississippi River Basin study unit.

Summary of river conditions within MWMO: Fertilizer and livestock manure were the predominant sources of nitrogen and phosphorus. These two sources comprised from 57 to 83 percent of the nitrogen and from 91 to 99 percent of the phosphorus in each of the four drainage basins. Municipal wastewater discharges comprise a larger nitrogen and phosphorus source in the Lower Mississippi River basin relative to the other drainage basins because of direct discharges to the Mississippi River from the TCMA treatment plants. Nitrogen and phosphorus yields in streams were greatest in the Minnesota and Lower Mississippi River basins, where amounts of nonpoint sources of these constituents also were the greatest per square mile.

Applicability of protocol to the MWMO: Study area included the MWMO area.

Overall relevance: High. Distribution of nutrient sources is relevant to the Lake Pepin eutrophication TMDL allocation process.

Kroening, S.E., Fallon, J.D., and Lee, K.E. (2000). Water-quality assessment of part of the Upper Mississippi River Basin, Minnesota and Wisconsin--Trace elements in streambed sediment and fish livers, 1995-96: U.S. Geological Survey Water-Resources Investigations Report 00-4031, 26 p. http://mn.usgs.gov/publicationIndex.html#m

Source, type, and purpose: USGS NAWQA report to describe the occurrence and distribution of trace elements, describe the relations to natural and anthropogenic factors, and describe any relation between concentrations in streambed sediment and fish livers.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Storm and industrial outfalls, fate and property of pollutants, and land use of contributing area. Sources of trace elements in urban areas leave higher concentrations in rivers that are within and downstream of urban areas.

Summary of monitoring protocols: USGS protocols for sampling fish and streambed sediment. Analyzed data using principal components analysis, a multivariate statistical technique. Monitoring for trace elements should not rely exclusively on streambed sediment or fish liver concentrations, as these were not correlated.

Summary of river conditions within MWMO: Concentrations of antimony, arsenic, cadmium, copper, lead, mercury, nickel, and zinc in streambed sediment were primarily related to urban land use. The greatest concentrations of most of these elements were measured in streambed sediment obtained from Shingle Creek, located within the MWMO area. In fish livers, all of the trace elements analyzed were detected except antimony, beryllium, cobalt, and uranium. There were no relations between trace element concentrations in fish livers and streambed sediment.

Applicability of protocol to the MWMO: Study area included the MWMO area, and protocol would be appropriate for fish or sediment sampling.

Overall relevance: Moderate. Assuming the MWMO will not conduct biological monitoring.

Lafrancois, B. Moraska and Glase, J. (2005). Aquatic studies in National Parks of the upper Great Lakes States: past efforts and future directions. Water Resources Division Technical Report, NPS/NRWRD/NRTR-2005/334. National Park Service, Denver, Colorado. http://www.nature.nps.gov/im/units/glkn/reports.htm

Source, type, and purpose: NPS report assessing extent and results of aquatic studies within the Great Lakes Network park units.

Applicable river reach: Water resources within the Great Lakes Networks parks, including the Mississippi River from Anoka to Hastings.

Applicable big river characteristics: Groundwater, flow rate, fate and properties of pollutants, and riparian vegetation. Aquatic resource health is based on the source, transport, and fate of pollutants.

Summary of monitoring protocols: Not applicable. Some entries include assessment of efficacy of monitoring.

Summary of river conditions within MWMO: Lafrancois and Glase offer a comprehensive summary of water resources studies within the national park units of the upper Midwest, including chapters on the Mississippi National River and Recreation Area and the Upper Mississippi National Water Quality Assessment (NAQWA) study by the U.S. Geological Survey. Each chapter summarizes existing research, highlights the strengths and weaknesses of the research, and makes recommendations for future monitoring and research. While not annotated, all literature includes full citation and tabulation of key information (sampling variables and frequencies, general approach, findings, and implications).

Applicability of protocol to the MWMO: The MWMO area is included within the study area.

Overall relevance: High. Comprehensive compilation of aquatic research literature which summarizes resource conditions and recommends monitoring improvements.

Ledder, T. (2003). Water resource information and assessment report for the Great Lakes Inventory and Monitoring Network. National Park Service, Great Lakes Inventory and Monitoring Network, Ashland, Wisconsin. Great Lakes Network Technical Report: GLKN/2003/05. 42p. http://www1.nature.nps.gov/im/units/glkn/Water resource information and assessment.pdf

Source, type, and purpose: National Park Service (NPS) report assessing current status of water resources within the Great Lakes Network (GLKN) park units.

Applicable river reach: Great Lakes Network parks, including the Mississippi River from Anoka to Hastings.

Applicable big river characteristics: Storm outfalls, atmospheric deposition, wastewater treatment facilities, and land use of contributing area. A variety of physical and chemical sources influence the water quality of park resources.

Summary of monitoring protocols: Not applicable.

Summary of river conditions within MWMO: NPS mandates pertaining to water quality and water quality standards of the four network states--Indiana, Michigan, Minnesota, and Wisconsin--were reviewed and summarized. Other materials reviewed include park "Baseline Water Quality Data Inventory and Analysis" reports, available park resource management reports, Internet websites for state lists of impaired water bodies (303(d) lists), the Great Lakes Agreement, and NPS. The water resources of the Mississippi National River and Recreation Area were listed as: heavily impacted by industrial/municipal waste water discharges, storm water runoff, commercial and residential development, contaminated sediments, and erosion. The report includes recommendations for monitoring protocols.

Applicability of protocol to the MWMO: The MWMO area is included within the study area.

Overall relevance: Moderate. Provides status of the Mississippi River with respect to state and federal water quality standards.

Lee, K.E., and Anderson, J.P. (1998). Water-Quality Assessment of the Upper Mississippi River Basin, Minnesota and Wisconsin--Polychlorinated Biphenyls in Common Carp and Walleye Fillets, 1975-95: U.S. Geological Survey Water-Resources Investigations Report 98-4126, 27 p. http://mn.usgs.gov/pubs/pcb/pcb.htm

Source, type, and purpose: USGS NAWQA report to summarize the spatial and temporal distribution of polychlorinated biphenyls (PCBs) and lipid-normalized PCBs (LNPCBs) in common carp and walleye fillets.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Tributaries, industrial outfalls, and fate and properties of pollutants. Hydrophobic compounds like PCBs resist decomposition and persist in the natural environment. Monitoring strategy may need to take into account compounds that were banned decades ago.

Summary of monitoring protocols: State protocols (Minnesota and Wisconsin) for PCBs in fish tissue.

Summary of river conditions within MWMO: LNPCB concentrations in common carp and walleye at those stream segments upstream or outside the TCMA were generally lower than those in UMR segments within the TCMA. The spatial distribution of PCB and LNPCB concentrations in common carp and walleye correspond with historical point and nonpoint source PCB inputs in the densely populated TCMA, and concentrations in fish were greater in areas that historically had elevated PCB concentrations in bed sediment. Although, PCB concentrations have decreased during 1975-95, low concentrations of PCBs still remain in the aquatic environment despite the fact that PCBs were banned nearly 20 years ago.

Applicability of protocol to the MWMO: Study area included the MWMO area. Protocol would be appropriate if MWMO plans to sample fish for PCBs.

Overall relevance: Low. Assuming the MWMO does not plan on biological monitoring.

Lubinski, K.S. (2004). Large river conceptual model. *in* S. Gucciardo, B. Route, and J. Elias, editors. Conceptual Ecosystem Models for the Great Lakes Network. GLKN/2004/04. http://www1.nature.nps.gov/im/units/glkn/

Source, type, and purpose: NPS report to present a brief scientific description about large Midwestern river ecosystems, using a diagrammatic conceptual modeling approach that focuses on stressors. This report is not, however, intended to present regional details about the riverine park units or to rank the drivers and stressors by their level of importance.

Applicable river reach: Large rivers, in general.

Applicable big river characteristics: Tributaries, lock-and-dams, vessel traffic, and land use of contributing area. Human behaviors upstream of and within large rivers are primary anthropogenic stressors.

Summary of monitoring protocols: Not applicable.

Summary of river conditions within MWMO: The model is a synthesis of current scientific understanding, field observations, and professional judgments regarding large river ecosystems. The report includes suggestions about potential focal points of future monitoring programs at the riverine park units, including native species, floodplain/channel physiography, water flow, and water quality.

Applicability of protocol to the MWMO: The Mississippi River within the MWMO area is a large Midwestern river ecosystem.

Overall relevance: High. Report offers comprehensive conceptual model of the ecological drivers and stressors of large rivers.

Magdalene, S., Engstrom, D., and Elias. J. (2007). Large rivers water quality monitoring protocol. Version 1.0. National Park Service, Great Lakes Network, Ashland, Wisconsin.

Source, type, and purpose: NPS monitoring protocol developed to assess park units centered on large rivers.

Applicable river reach: Entire mainstems of the Namekagon and St. Croix Rivers, mainstem of the Mississippi River between its confluence with the Crow River and Hastings, Minnesota.

Applicable big river characteristics: Tributaries, nutrient cycling, and land use of contributing area. In a large river system, tributaries are the primary inputs of nutrients, based on the land uses of the subwatersheds.

Summary of monitoring protocols: NPS protocol development to assess water quality status and trends of large rivers. This protocol evaluates the applicability of the two leading monitoring strategies, targeted sampling and probability sampling, to NPS monitoring goals for two parks centered on large, non-wadeable rivers: the Mississippi National River and Recreation Area and the St. Croix Wild and Scenic Riverway. The recommended monitoring protocol takes into account the current monitoring conducted by other water resource agencies, to minimize duplication and maximize budget. Protocol includes maps showing recommended sampling sites, plus standard operating procedures for all steps of the protocol (e.g., site establishment, field sampling, sample processing, data management and analysis, and revising the protocol).

Summary of river conditions within MWMO: Site selection based on the range of variability observed (low: pH, moderate: DO, high: TP) in historical water quality data.

Applicability of protocol to the MWMO: The MWO area was included within the study area.

Overall relevance: High. Report gives concise comparison of the two leading monitoring strategies employed by federal agencies.

McDonald, M.E., Paulsen, S., Blair, R., Dlugosz, J., Hale, S., Hedtke, S., Heggem, D., Jackson, L., Jones, K.B., Levinson, B., Olsen, A., Stoddard, J., Summers, K., and Veith, G. (2002). Research strategy of the Environmental Monitoring and Assessment Program (EMAP). EPA 620/R-02/002. http://www.epa.gov/emap/html/pubs/docs/resdocs/EMAP_Research_Strategy.pdf

Source, type, and purpose: U.S. EPA report to explain and advocate for "the only statistically-valid means of assessing the condition of all waters."

Applicable river reach: All water resources within the U.S.

Applicable big river characteristics: Tributaries, flow rate, and field conditions. The average condition of an entire watershed is based on broad factors such as flow.

Summary of monitoring protocols: U.S. EPA strategy for the development of long-term monitoring protocols. Environmental Monitoring and Assessment Program (EMAP) is a long-term research effort to enable status and trend assessments of aquatic ecosystems across the U.S. with a known statistical confidence. EMAP focuses on developing indicators and unbiased statistical design frameworks to assess the status and trends of aquatic ecosystems. The goal of the research strategy is the development of consistent scientific approaches to determine the health of the nation's aquatic ecosystems and identify the stressors most closely associated with impairment. These efforts allow for the first regional comparisons of aquatic ecosystem conditions across the entire U.S., improving the quality of performance-based reporting to Congress.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: Although this is one of the leading monitoring protocol development methods, it may not be feasible to employ within the MWMO, given the variability of monitoring parameters within the relatively-small MWMO area.

Overall relevance: High. The MWMO should consider statistically-designed monitoring.

McNellis, R.P., Fallon, J.D., and Lee, K.E. (2001). Water quality assessment of part of the Upper Mississippi River Basin, Minnesota and Wisconsin--Organochlorine compounds in streambed sediments and fish tissues, 1995-1997. USGS WRIR 00-4213, 10 pp. mn.usgs.gov/pubs/00-4213.pdf

Source, type, and purpose: USGS NAWQA report to assess the presence and distribution of organochlorine compounds (OCs) including polychlorinated biphenyls (PCBs).

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Tributaries, fate and property of pollutants, and land use of contributing area. OCs have frequently been used as pesticides in agricultural and urban areas, but generally had fewer applications in forested environments.

Summary of monitoring protocols: USGS protocols for sampling organic compounds in streambed sediments and fish tissues. Organochlorines sometimes found in fish but not sediments from a given site. Both measures may be needed, to be robust indication of contaminant presence in biota.

Summary of river conditions within MWMO: A total of 13 OCs were detected among 14 of 27 streambed sediment sampling locations. Eight OCs were detected in both fish and streambed sediment samples. OC concentrations in fish tissue tended to increase in a downstream direction on the Mississippi River. The forest sites had fewer detections than the other land uses. No OCs were detected in streambed sediment at agricultural sites; however, the agricultural sites had 17 detections of OCs in fish tissue. Total DDT was the only OC within an urban land use that exceeded guidelines for piscivorous wildlife.

Applicability of protocol to the MWMO: Study area includes the MWMO area. Protocol would be appropriate if MWMO plans to sample fish for OCs.

Overall relevance: Low. Assuming the MWMO does not plan on biological monitoring.

Metropolitan Council (2005). Water Resources Management Policy Plan, Regional Report Number 32-04-065, Metropolitan Council Environmental Services, St. Paul, Minnesota.
http://www.metrocouncil.org/planning/environment/WRMPP/WRMPP2005.htm

Source, type, and purpose: Metropolitan Council report on integrating water resources protection and management with planning for the region's growth, containing guidelines for developing and maintaining service systems that support development and for which the Council has some statutory responsibility, including wastewater service, surface water management and regional water supply.

Applicable river reach: Water resources within the seven-county Twin Cities Metropolitan Area (TCMA).

Applicable big river characteristics: Tributaries, WWTFs, and land use of contributing areas. Anthropogenic stressors on the large rivers of the region will increase as the population increases.

Summary of monitoring protocols: Not applicable. Report contains policy statements and implementation strategies.

Summary of river conditions within MWMO: The region is projected to grow in population from 2.6 million people in 2000 to 3.6 million in 2030.

Applicability of protocol to the MWMO: The MWMO area is included within the TCMA.

Overall relevance: Moderate. Delineates policy framework of most active monitoring agency within the TCMA, including the most sites on the Mississippi River in this area.

Metropolitan Council Environmental Services (2003). Quality Assurance Program Plan: Stream Monitoring, Metropolitan Council Environmental Services, Water Resources Assessment Section, St. Paul, Minnesota.
http://www.metrocouncil.org/environment/RiversLakes/Streams/Stream%20Monitoring%20QAPP_Final.pdf

Source, type, and purpose: MCES protocol for stream monitoring, to determine the extent of nonpoint source pollutant loading from tributaries to the Mississippi, Minnesota, and St. Croix Rivers, to provide the information necessary for development of target pollutant loads for these tributary watersheds, and to measure progress toward achieving the target pollution loads.

Applicable river reach: Any tributary stream within the seven-county Twin Cities Metropolitan Area, along with several streams in the Lower Minnesota River and Mankato areas.

Applicable big river characteristics: Flow rate, tributaries, and land use of contributing area. Stormwater runoff in both urban and rural areas carries nonpoint source pollutants from diverse and widely scattered sources to Metropolitan Area streams and rivers, and stream monitoring is conducted to determine the extent of nonpoint source pollutant loading.

Summary of monitoring protocols: MCES protocol used by the Watershed Outlet Monitoring Program (WOMP) for determining annual loads from urban and semi-urban subwatersheds. Automated measurements of water stage, in conjunction with site-specific rating curves, are used to estimate flow rates in all streams. During runoff events, automated water samples and occasional grab samples are obtained, and during baseflow conditions grab samples are obtained, for laboratory analysis of a variety of nonpoint source pollutants, including metals, nutrients, sediments, and biota.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: This protocol is used for the MCES Watershed Outlet Monitoring Program sites on Shingle and Bassett Creeks.

Overall relevance: High. An excellent local example of comprehensive monitoring program for physical, chemical, and biological parameters sampled with sufficient frequency to generate annual loads.

Minnesota Department of Agriculture (2006). Surface water monitoring work plan. Minnesota Department of Agriculture, St. Paul, MN, 22 pp.
http://www.mda.state.mn.us/chemicals/pesticides/maace.htm

Source, type, and purpose: MDA work plan for pesticide monitoring program: to measure pesticide and nutrient concentrations in representative streams and rivers in agricultural and urban areas of Minnesota, and to report on detection frequencies of pesticides as required by Minnesota law.

Applicable river reach: Surface waters within the state of Minnesota that are known to be susceptible to pesticide contamination.

Applicable big river characteristics: Tributaries and land use of contributing area. Extensive water resources in Minnesota are susceptible to pesticide contamination and some streams have demonstrated the potential to exceed standards or other relevant numeric criteria.

Summary of monitoring protocols: Appendix B of the report contains monitoring protocol: selected streams are grab-sampled 4-6 times each year during the summer months (May-August), with some attempt to capture a range of baseflow and peak flows.

Summary of river conditions within MWMO: Not applicable. Supplementary publication of 2006 monitoring data indicates detections of atrazine (especially early summer storms) and acid pesticides (especially baseflow) in Bassett Creek.

Applicability of protocol to the MWMO: MWMO may want to expand this approach to Shingle Creek, given the findings that agricultural pesticides are delivered by wet and dry deposition to the western metropolitan suburbs (Capel et al. 1998).

Overall relevance: Moderate. Best local example of on-going pesticides monitoring.

Minnesota Department of Health (2001). Source water assessment for the City of Minneapolis public water supply. 9 pp. http://mdh-agua.health.state.mn.us/swa/pdwgetpws.cfm

Source, type, and purpose: MDH report to provide Minneapolis drinking water customers with 1) a general description of the area which supplies water to the Minneapolis Water Works; 2) an overview of why this water supply is susceptible to potential contaminants; 3) a description of the contaminants of concern which may impact the users of the public water supply; and 4) to the extent practical, the origins of the contaminants of concern.

Applicable river reach: Mississippi River above Fridley, Minnesota.

Applicable big river characteristics: Pollutant properties, nutrient cycling, water appropriations, and land use of contributing area. The large quantities and flow rate of water in the Mississippi River helps attenuate contaminants. Other factors influencing the sensitivity of the river include climate seasonality, topography, hydrology, geology, vegetation, and the distribution of various soil types within the subwatersheds of the Mississippi River.

Summary of monitoring protocols: U.S. EPA requirements to monitor contaminants regulated under the federal Safe Drinking Water Act (SDWA). The Minneapolis Water Works has identified pharmaceuticals and endocrine disrupting chemicals as emerging issues, but of greatest concern are petroleum products, pesticides, microorganisms, and nutrients.

Summary of river conditions within MWMO: Typical draw from the river by the Minneapolis Water Works is 65 million gallons per day, or less than 2-percent of the flow (3.9 billion gallons per day). For the past four years during the period of May-June, the MDH has conducted a limited study at the Minneapolis intake for all of the SDWA pesticides and nitrates. The results of sampling for pesticides/nitrates have not indicated any problems during the sampling period. However, nearly two-thirds of Upper Mississippi River basin sites monitored by the MPCA had threatened water quality or did not support the designated use. Most monitoring upstream of the public water system intake is generally related to swimmable and fishable goals. A greater emphasis on drinking water standards in the future would be beneficial. The Sauk and Crow Rivers in particular are significant contributors of contaminants to the Mississippi River.

Applicability of protocol to the MWMO: The source water assessment area extends down to the intakes in Fridley, immediate upstream of the MWMO.

Overall relevance: High. Drinking water source protection is the first and foremost goal of resource management.

Minnesota Pollution Control Agency (planned). Major Watershed Outlet Monitoring Protocol.

Contact: Craig Affeldt, Minnesota Pollution Control Agency, 651-296-6062

Source, type, and purpose: Planned MPCA program to monitor USGS HUC-8 outlets. 25 out of 80 sites have been selected to be monitored, with all 80 to be eventually monitored.

Applicable river reach: Not applicable.

Applicable big river characteristics: Not applicable.

Summary of monitoring protocols: Not applicable.

Summary of river conditions within MWMO:. Not applicable.

Applicability of protocol to the MWMO:. Not applicable.

Overall relevance: Moderate. None of the initially selected 25 sites are within the MWMO, but the 80 sites cover the entire state.

Minnesota Pollution Control Agency (2006). Work Plan-II of the Lake Pepin Watershed TMDL Project for Eutrophication & Turbidity Impairments. Minnesota Pollution Control Agency, St. Paul, MN. 24 pp. http://www.pca.state.mn.us/water/tmdl/tmdl-lakepepin.html#products

Source, type, and purpose: MPCA update to the original Lake Pepin TMDL work plan (MPCA 2005).

Applicable river reach: Minnesota River Basin; Upper Mississippi River Basin upstream of Anoka; the St. Croix River Basin; rivers and streams within the Twin Cities Metropolitan Area; and remaining smaller tributaries.

Applicable big river characteristics: Tributaries, flow rate, suspended sediment, nutrient cycling, and land use of contributing area. As flows decrease, and Lake Pepin residence time lengthens, environmental stress from natural and anthropogenic sources increases. Monitoring strategy needs to account for variety of land uses of large drainage area.

Summary of monitoring protocols: Not applicable.

Summary of river conditions within MWMO: Whereas the first work plan and RFP focused to a large extent on ambient water quality issues in the Mississippi River, Spring Lake, and Lake Pepin, this second work plan focuses on the need to provide input data for the model that is being developed by Limno-Tech, Inc., to evaluate water quality conditions in the Mississippi River from Lock & Dam 1 through Lake Pepin. This three-dimensional model, called ECOM/SED-RCA, combines hydrodynamic, sediment transport and water quality components into an integrated modeling system.

Applicability of protocol to the MWMO: Lake Pepin is the receiving waters for the MWMO area.

Overall relevance: High. The MWMO will likely be affected by the Lake Pepin TMDL allocation process.

Minnesota Pollution Control Agency (2005). Work Plan of the Lake Pepin Watershed TMDL Project for Eutrophication & Turbidity Impairments. Minnesota Pollution Control Agency, St. Paul, MN. 49 pp. http://www.pca.state.mn.us/water/tmdl/tmdl-lakepepin.html#products

Source, type, and purpose: MPCA work plan for the Lake Pepin TMDL process, as required by the U.S. EPA.

Applicable river reach: Minnesota River Basin; Upper Mississippi River Basin upstream of Anoka; the St. Croix River Basin; rivers and streams within the Twin Cities Metropolitan Area; and remaining smaller tributaries.

Applicable big river characteristics: Tributaries, flow rate, suspended sediment, nutrient cycling, and land use of contributing area. As flows decrease, and Lake Pepin residence time lengthens, environmental stress from natural and anthropogenic sources increases. Monitoring strategy needs to account for variety of land uses of large drainage area.

Summary of monitoring protocols: Not applicable.

Summary of river conditions within MWMO: Lake Pepin is federally listed as a 303(d) Impaired Waters for two impairments – turbidity and eutrophication. The Lake Pepin Watershed Total Maximum Daily Load (TMDL) project includes two hypereutrophic lakes – Lake Pepin and Spring Lake – and a chronically turbid segment of the Mississippi River, roughly from mid-Lake Pepin upstream to the confluence with the Minnesota River. The Lake Pepin Watershed TMDL will establish Waste Load Allocations (for point sources) and Load Allocations (for nonpoint sources) at a fairly high level of aggregation for the above listed reaches.

Applicability of protocol to the MWMO: Lake Pepin is the receiving waters for the MWMO area.

Overall relevance: High. The MWMO will likely be affected by the Lake Pepin TMDL allocation process.

Minnesota Pollution Control Agency (2004). Guidance Manual for Assessing the Quality of Minnesota Surface Waters for the Determination of Impairment. St. Paul, Minnesota, 99 pp. + appendices. www.pca.state.mn.us/publications/manuals/tmdl-guidancemanual04.pdf

Source, type, and purpose: MPCA report 1) to consolidate the existing protocols into one document, 2) to define the data and information requirements needed to determine impairment for the various categories of pollutants, and 3) to provide a rationale for the thresholds selected that indicate impairment.

Applicable river reach: All surface waters within Minnesota.

Applicable big river characteristics: Tributaries, suspended sediment, and nutrient cycling. Each reach of a stream or river responds differently to upstream inputs, based on factors within that particular reach.

Summary of monitoring protocols: MPCA protocol for assessment of impaired waters. This report describes the data requirements and determination of impaired condition for narrative and non-impairment water quality standards, and for pollutants with numeric water quality standards based on toxicity, human health, and wildlife.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: The MWMO's stretch of the Mississippi River has been assessed as impaired waters.

Overall relevance: Moderate. The method used to assess the MWMO area for impairment status should be useful to the MWMO.

Minnesota Pollution Control Agency (2003). Volunteer Surface Water Monitoring Guide. St. Paul, Minnesota, 84 pp. http://www.pca.state.mn.us/water/monitoring-guide.html

Source, type, and purpose: MPCA guidelines for volunteer water monitors.

Applicable river reach: All surface waters within Minnesota.

Applicable big river characteristics: Tributaries, field conditions, and suspended sediment. Fundamental conditions of a water resource are appropriate water quality indicators for volunteer monitoring.

Summary of monitoring protocols: MPCA protocol for volunteer monitoring of the quality of surface waters. In Minnesota, volunteers have responded generously and enthusiastically with their time and energy. Volunteer citizen water monitoring is a critical component in educating Minnesotans about water quality issues. When volunteers design a monitoring process that has appropriate methods built into it, their data will then have the "rigor" to establish scientific credibility. That data can then be entered into an environmental database and used for making decisions. This guide introduces volunteers to key concepts such as monitoring design, selecting a contract laboratory, data quality and management, getting information out of data, and evaluating monitoring program performance.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: The MWMO could engage volunteer monitors to track water quality issues of public interest.

Overall relevance: Moderate. Approachable and comprehensive guideline for monitoring design.

Minnesota Pollution Control Agency (2003). Upper Mississippi River Basin Water Quality Plan: Headwaters to Rum River - Anoka.
http://www.pca.state.mn.us/water/basins/uppermiss/

Source, type, and purpose: MPCA report to identify water quality management needs.

Applicable river reach: Mississippi River basin above its confluence with the St. Croix River (not including the Minnesota River basin).

Applicable big river characteristics: Nutrient cycling, stormwater outfalls, and WWTPs. **Summary of monitoring protocols:** Not applicable.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: This report is limited to the Mississippi River basin above Anoka, MN.

Overall relevance: Low. Report summarizes key water quality management concerns for the Mississippi River basin above the MWMO.

Mistry, J., Simpson, M., Berardi, A., and Sandy, Y. (2004). Exploring the links between natural resource use and biophysical status in the waterways of the North Rupununi, Guyana. Journal of Environmental Management 72: 117-131.
http://oro.open.ac.uk/174/01/Mistry_et_al-2004_Exploring_the_links.pdf

Source, type, and purpose: Academic journal article to develop a methodological and technological framework for engaging stakeholders in a common, participatory decision-making process for monitoring and sustainable natural resource management..

Applicable river reach: Major rivers of Guyana.

Applicable big river characteristics: Field conditions, suspended sediment, and nutrient cycling. The North Rupununi District in southwest Guyana is comprised of a mosaic of ecosystems, including savannas, wetlands and forests, and is home to the Makushi Amerindians. With logging and mining seen as increasing threats to the region, it is necessary to look at methods for engaging stakeholders in monitoring the status of their natural resources.

Summary of monitoring protocols: Research methods included informal interviews, the use of the River Habitat Survey (RHS), and water quality measurements. The results indicate the heavy reliance of the Makushi on the waterways for their daily lives, particularly for fishing. A monitoring scheme was set up using this study's outputs as a baseline from which any future changes can be compared. Further work is to be carried out over the next three years to produce monitoring and sustainable management procedures for the North Rupununi ecosystems.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: The MWMO can consider methods to engage stakeholders in resource management.

Overall relevance: Low. Protocol is poorly documented.

Morlock, S.E., Nguyen, H.T., and Ross, J.H. (2002). Feasibility of acoustic doppler velocity meters for the production of discharge records from U.S. Geological Survey streamflow-gaging stations. U.S. Geological Survey Water Resources Investigations Report 01-4157, 56 pp.

Source, type, and purpose: USGS report on a study to assess the quality of acoustic doppler velocity meter (ADVM) data.

Applicable river reach: Three long-term gaging stations on the Kankakee River, Fall Creek, Iroquois River in Indiana.

Applicable big river characteristics: Flow rate and suspended sediments. Complex flow conditions at many potential streamflow-gaging stations may negate stable stage-discharge ratings and make the use of conventional methods impractical or impossible.

Summary of monitoring protocols: Development of USGS protocol to measure stream and river discharge using ADVM technology, requiring a thorough survey of the gage location. Meters measure the velocity of particulates suspended in the water, capturing the Doppler shift of backscatter from two acoustic beams. Report gives recommendations for avoiding acoustic beam interference.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: An ADVM could be installed on any of a number of Mississippi bridges within the MWMO area. Bridges immediately downstream of a lock-and-dam (e.g, Third Avenue bridge, Stone Arch bridge, or I-35 bridge), are probably not appropriate for this method, due to pervasive turbulence.

Overall relevance: High. The MWMO needs to accurately document the discharges of the Mississippi River as it enters and leaves the MWMO, to enable TMDL load calculations.

Oakley, K.L., Thomas, L.P., and Fancy, S.G. (2003). Guidelines for long-term monitoring protocols. Wildlife Society Bulletin 31:100-1003. http://science.nature.nps.gov/im/monitor/protocols/protocolguidelines.pdf.

Source, type, and purpose: NPS published journal article to present guidelines for developing the content and format of long-term monitoring protocols.

Applicable river reach: All natural resources of the U.S.

Applicable big river characteristics: Tributaries, and field conditions. The overall condition of a resource can be determined from appropriately justified monitoring variables.

Summary of monitoring protocols: NPS and USGS protocol development guidelines for long-term monitoring. Monitoring protocols are detailed study plans that explain how data are to be collected, managed, analyzed, and reported, and are a key component of quality assurance for natural resource monitoring programs. Protocols are necessary to ensure that changes detected by monitoring actually are occurring in nature and not simply a result of measurements taken by different people or in slightly different ways. The authors have developed guidelines for the recommended content monitoring protocols, including a narrative that documents the protocol development process, and a number of standard operating procedures. The National Park Service and United States Geological Survey have adopted these guidelines to assist scientists developing protocols for more than 270 national park units.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: If the MWMO plans to develop/update its monitoring plan, this is where they should start.

Overall relevance: High. Presents concise outline template of any proposed monitoring protocol.

Payne, G.A., Ayers, M.A., and Brown, R.G. (1982). Quality of runoff from small watersheds in the Twin Cities Metropolitan Area, Minnesota—Hydrologic data for 1980. U.S. Geological survey Open-File Report 82-504. 289 pp. [Note: First 29 pages scanned into pdf file, remaining 260 pages of document (not scanned) were detailed appendix of data, available on USEPA's STORET database.]

Source, type, and purpose: USGS report to describe approach and methods used to collect water flow and quality data, which will be used to quantify and characterize storm and annual nonpoint source loads from representative subwatersheds.

Applicable river reach: Several rivers, streams, and storm sewers within the seven-county Twin Cities Metropolitan Area.

Applicable big river characteristics: Precipitation, tributaries, and storm outfalls. Runoff concentrations from basins with similar characteristics varies considerably from one area to another and one storm to another, therefore monitoring strategy should include intensive and continuous sampling to derive accurate annual loads for a given location.

Summary of monitoring protocols: USGS protocols based on anticipated speed of hydrologic response, with stage recorders at most sites, and a combination of manual grab and automated sampling. Primary emphasis was on analysis of samples for suspended solids, nutrients, and oxygen-demanding substances, with secondary emphasis on chloride, metals, bacteria, pesticides, and PCBs.

Summary of river conditions within MWMO: An intensive study of storm runoff was conducted at 19 sites in the seven-county Twin Cities Metropolitan Area during 1980, including 7-8 sites in or near the MWMO area. This large document contains extensive tables of water flow and chemistry data, but no analysis or interpretation of the data, which was published as Ayers et al. (1985).

Applicability of protocol to the MWMO: This was an early attempt at obtaining subwatershed annual loading data. Some of the field methods and many of the laboratory methods have been improved since this time. However, the data (if still available) should provide a useful historical perspective to current water quality conditions.

Overall relevance: Moderate. Methods outmoded, but historical data for MWMO area.

Shelton, L.R. and Capel, P.D. (1994). Guidelines for collecting and processing samples of stream bed sediment for analysis of trace elements and organic contaminants for the National Water-Quality Assessment program. U.S. Geological survey Open-File Report 94-458.
http://ca.water.usgs.gov/pnsp/pest.rep/bs-t.html

Source, type, and purpose: USGS report on stream bed sediment monitoring protocol.

Applicable river reach: All streams and rivers within the U.S.

Applicable big river characteristics: Substrate properties and land use of contributing area. Fine-grained particles and organic matter are natural accumulators of trace elements and hydrophobic organic contaminants in streams. Non-point contributions may be intermittent within the water column; bed sediments in depositional environments of streams provide a time-integrated sample of these contaminants. Combined with tissue samples, bed sediments provide a useful measure of the potential bioaccumulation of these contaminants.

Summary of monitoring protocols: USGS protocol for sampling bed sediments in two phases: 1) an Occurrence Survey of 15-20 sites per NAWQA study area to assess priority pollutants, and 2) a Spatial Distribution Survey of 20-30 sites to provide better geographic coverage of the priority pollutants identified in the Occurrence Survey. Protocol recommends compositing samples from 5-10 depositional areas for each 100-meter-reach site.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: Method is possible for the Mississippi River within the MWMO area, but requires identification of low energy depositional areas, inside a meander bend or behind flow obstructions or in near-shore shallows.

Overall relevance: Moderate. Due to its temporal integration, method is best employed intermittently and the MWMO may want to let other water agencies (i.e., USGS) conduct these surveys.

Soballe, D.M. and Fischer, J.R. (2004). Long Term Resource Monitoring Program Procedures: Water quality monitoring. U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin, March 2004. Technical Report LTRMP 2004-T002-1 (Ref. 95-P002-5). 73 pp. + Appendixes A–J

Source, type, and purpose: USGS report to document the water quality sampling and analysis techniques employed by a long-term monitoring program.

Applicable river reach: Six pools within the Upper Mississippi and Illinois Rivers.

Applicable big river characteristics: Channel type, primary productivity, lock-and-dams, and land use of contributing area. The suitability of Mississippi River pools as habitat for aquatic organisms depends upon processes within these riverine lakes that incorporate upstream water quality.

Summary of monitoring protocols: The LTRMP sampling design employs both fixed site and stratified random sampling; monitoring protocols are those standardized by USGS, U.S. EPA, and APHA.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: Program monitors pools within the Upper Mississippi River (including Lake Pepin, Pool 4); the MWMO area includes Pool 1 of the Mississippi River.

Overall relevance: High. Long-term monitoring program and data base.

Stark, J.R. (1997). Causes of variations in water quality and aquatic ecology in rivers of the Upper Mississippi River Basin, Minnesota and Wisconsin: U.S. Geological Survey Fact Sheet FS-249-96, 4 p.

Source, type, and purpose: USGS fact sheet to assess natural and anthropogenic influences on water quality of the major rivers in a portion of the Upper Mississippi River basin.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Precipitation, flow rate, lock-and-dams, and land use of contributing area. Natural and human factors (including climate, hydrology, geology, soils, land use, land cover, water management, and water use) affect water quality and aquatic ecology in rivers and streams in the Upper Mississippi River Basin.

Summary of monitoring protocols: USGS protocols for water quality sampling of large rivers.

Summary of river conditions within MWMO: Sediments and nutrients highest in the Mississippi River below the Minnesota River. Heavy metals (Cd, Pb, and Hg) were greatest in Mississippi River sediments downstream of Twin Cities. Fecal coliform bacteria concentrations in the Mississippi River sometimes exceed EPA standards. Human use of the land has accentuated natural differences in water quality and ecological conditions in each of the three major rivers in the Upper Mississippi River Basin.

Applicability of protocol to the MWMO: The MWMO is included within the study area.

Overall relevance: Moderate. Presents an overview of conditions and potential sources of variability of water quality in the region.

Stark, J.R., Fallon, J.D., Fong, A.F., Goldstein, R.M., Hanson, P.E., Kroening, S.E., and Lee, K.E. (1999). Water-quality assessment of part of the Upper Mississippi River Basin, Minnesota and Wisconsin--design and implementation of water-quality studies, 1995-98: U.S. Geological Survey--Water-Resources Investigations Report 99-4135, 85 p. http://mn.usgs.gov/publicationIndex.html#m

Source, type, and purpose: USGS report to describe the study design and implementation for the first intensive phase of the Upper Mississippi River NAWQA study.

Applicable river reach: Mississippi River basin above Lake Pepin.

Applicable big river characteristics: Tributaries, groundwater discharge, pollutant properties, and land use of contributing area. Contaminants are transported from land surface to the ground-water flow system and from the ground-water flow system to streams. Trace elements and hydrophobic organic compounds tend to accumulate in streambed sediments and fish tissue rather than in water. Monitoring strategy should account for pollutants of the contributing land area and the potential pathways for reaching streams.

Summary of monitoring protocols: USGS development of monitoring protocols for a strategy of intensive sampling within a NAWQA study area. The natural and human factors that are responsible for most of the variation of water quality throughout the UMIS were identified. The geographic distributions of the most influential natural and human factors were used to subdivide the study unit into major sub-areas that had relatively distinct environmental settings consisting of homogenous natural and human factors and that were expected to have similar water quality. The monitoring strategy consisted of surface-water, ground-water, and aquatic-biological sampling at study-unit-wide, intermediate, and small scales, and addressed spatial and temporal aspects of water-quality conditions. Information for each sampling approach included the following: site-selection criteria, number of sites, types of samples, general sample collection methods, sampling frequency, characteristics measured, laboratory determined constituents, and the contributions of the sampling approach to an integrated water-quality assessment.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: The MWMO area is included within the study area. Protocol is appropriate for comparing the effect of different land uses on water quality.

Overall relevance: High. One of the primary monitoring protocols that has been successfully employed within the Upper Mississippi basin.

Stednick, J.D., and Gilbert, D.M. (1998). Water quality inventory protocol: riverine environments. National Park Service Technical Report NPS/NRWRD/NRTR-98/177. http://science.nature.nps.gov/im/monitor/protocols/wrdwq.wpd.

Source, type, and purpose: NPS report to develop monitoring protocol for lotic systems.

Applicable river reach: All streams and rivers within the U.S.

Applicable big river characteristics: Flow rate and tributaries. For riverine systems, the quality of water flowing past the sampling location is related to upstream conditions.

Summary of monitoring protocols: NPS protocol for stream sampling, with both broad and detailed descriptions of various aspects of stream and river monitoring. Protocol does not specify sampling frequencies for particular monitoring parameters, but recommends sampling methods and analytical techniques for selected parameters, including field parameters, nutrients, bacteria, and biota.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: While this protocol was written for National Park Service streams and rivers, including MNRRA, of which MWMO is a part, it has been superceded by updates, especially concerning quality assurance and quality control measures to ensure the data are meaningful, representative, complete, precise, accurate, comparable, and scientifically-defensible.

Overall relevance: Moderate. Protocol is a good overview of a general river protocol.

Stevens, D.L. Jr, and Olsen, A.R. (2004). Spatially balanced sampling of natural resources. Journal of the American Statistical Association 99(465):262-278.

Source, type, and purpose: Peer-reviewed paper to introduce the key concepts and issues of probability surveys.

Applicable river reach: All natural resources within the U.S.

Applicable big river characteristics: Tributaries, field conditions, and nutrient loading.

Summary of monitoring protocols: EPA protocol development concepts for probability sampling design. Olsen demonstrates that statistically-based probability surveys have advantages over past methods of survey design. Examples of probability survey designs are given for natural resources with three different geographic distributions: discrete points (0-D), linear (1-D), or areal (2-D). Simplified and more complex survey designs are presented, including discussion of competing monitoring objectives, stratification, unequal probability, and nested survey.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: Given the variability of quality of water resources within the MWMO area, and usual limitations of monitoring budgets, it may not be feasible to employ probability methods within the MWMO.

Overall relevance: High. Although it may not be feasible, this design method should be considered during the development of a monitoring program for the MWMO.

Talmadge, P.J., Lee, K.E., Goldstein, R.M., Anderson, J.P., and Fallon, J.D. (2000). Water quality, physical habitat, and fish-community composition in streams in the Twin Cities metropolitan area, 1997-1998.USGS WRIR 99-4247, 18 pp. http://mn.usgs.gov/publicationIndex.html#m

Source, type, and purpose: USGS report to characterize and identify factors that influence water quality and fish-community composition.

Applicable river reach: Thirteen streams of the Twin Cities Metropolitan Area (TCMA).

Applicable big river characteristics: Channel type, substrate properties, riparian vegetation, and land use of contributing area. Urbanization affects fish-community composition through hydrologic modifications, removal of habitat and cover, increased water temperatures, and increased inputs of ions such as sodium and chloride. Monitoring strategy should consider indicators of environmental setting.

Summary of monitoring protocols: USGS NAWQA protocols for water quality and fish sampling. Field measurements included physical habitat at stream transects, riparian cover, and channel sinuosity and gradient.

Summary of river conditions within MWMO: Changes in fish-community composition were associated with factors of urbanization: percentage of impervious cover, water chemistry (salts), water temperature, geomorphology, substrate, in-stream habitat, and migration barriers.

Applicability of protocol to the MWMO: Study sites included Shingle Creek and Basset Creek, which flow into the MWMO area. Protocol is appropriate for continued habitat assessment in these areas.

Overall relevance: High. Assuming MWMO is interested in habitat restoration.

U.S.A.C.E. (1995). Engineering and Design: Sedimentation Investigations of Rivers and Reservoirs. U.S. Army Corps of Engineers, Engineer Manual no. 1110-2-4000, 177 pp.

Source, type, and purpose: USACE protocol manual for evaluating sediment yield and sedimentation dynamics in rivers and reservoirs.

Applicable river reach: All rivers and reservoirs in the U.S.

Applicable big river characteristics: River channel geometry, substrate properties, suspended sediments, lock-and-dams, and bridge piers. The naturally-occurring channel shape and sediment transport mechanics must be adequately understood before the onset of an engineering project. Sedimentation problems arise when the project design ignores the impact of upstream sediment transport into the project area, or lacks provisions to maintain appropriate amounts of downstream sediment transport away from the project area.

Summary of monitoring protocols: The original 1989 version of the protocol describes how to

identify, document, and control sedimentation problems associated with engineering project activities. Protocol focuses on physical (not chemical or biological) aspects of sedimentation. The update for the 1995 version adds sediment properties, measurement techniques, transport mechanics, and model selection recommendations.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: This protocol fits the spatial scale of the Mississippi River within the MWMO area: a large meandering river that includes bridges and navigational structures to maintain run-of-the-river. Protocol does not evaluate the chemical or biological aspects of sedimentation problems, but presents the methods needed to understand physical sedimentation processes. Protocol could be used to assess sediment transport within the MWMO.

Overall relevance: High. USACE is active within the MWMO reach, and is reputable source of information for physical sedimentation analysis techniques.

U.S.E.P.A. (2000). Methods for measuring the toxicity and bioaccumulation of sediment-associated contaminants with freshwater invertebrates - Second edition. U.S. Environmental Protection Agency Report no. 600/R-99/064.

Source, type, and purpose: USEPA report on protocol for collecting freshwater invertebrates to assess resource contamination and potential adverse effects to aquatic organisms.

Applicable river reach: All rivers and streams in the U.S.

Applicable big river characteristics: Substrate properties and land use of contributing area. Sediment provides habitat for many aquatic organisms and is a major repository for many of the more persistent chemicals that are introduced into surface waters. Contaminated sediments may be directly toxic to aquatic life or can be a source of contaminants for bioaccumulation in the food chain. In-place contaminated sediment can result in depauperate benthic communities, while disposal of contaminated dredged material can potentially exert adverse effects on both pelagic and benthic systems.

Summary of monitoring protocols: This manual describes procedures for testing freshwater organisms in the laboratory to evaluate the potential toxicity or bioaccumulation of chemicals associated with whole sediments. Sediments may be collected from the field or spiked with compounds in the laboratory. Toxicity methods are outlined for two organisms, the

amphipod Hyalella azteca and the midge Chironomus tentans. Methods are described for conducting 10-d toxicity tests with amphipods or midges.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: Method is employed by the MCES within the MWMO area.

Overall relevance: High. Monitoring agencies are moving beyond contaminant detection and ranges of concentrations to assessments of bioavailability.

U.S.G.S. (variously dated). Applications of Hydraulics: Surface water techniques. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, chaps. A1-A21. http://pubs.usgs.gov/twri/ [Not available in paper; chapters available on-line.]

Source, type, and purpose: USGS compilation of consistent methods for measuring and analyzing surface water flow rates.

Applicable river reach: All rivers and streams in the U.S.

Applicable big river characteristics: Flow rate and river channel geometry. The design of streamflow networks is governed to some extent by the ability to measure stage and discharge at a given site, depending on geology and topography, to the required degree of accuracy.

Summary of monitoring protocols: TWRI Book 3 contains 21 chapters, including: the general procedure for gaging streams (Chapter A6), stage measurement at gaging stations (Chapter A7), discharge measurements at gaging stations (Chapter A8), measurement of time of travel in streams by dye tracing (Chapter A9), discharge ratings at gaging stations (Chapter A10), computation of continuous records of streamflow (Chapter A13), and acoustic velocity meter systems (Chapter A17). A continuous record of stage is obtained by installing instruments that sense and record the water-surface elevation in the stream. Discharge measurements are initially made at various stages to define the relation between stage height and discharge rate. The continued development of new instrumentation and analytical techniques has improved the capability of obtaining streamflow records under challenging conditions.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: These protocols could be used to gage and analyze the full range of flow volumes observed within the MWMO, from stormwater outflows to the mainstem Mississippi.

Overall relevance: High. The USGS is the expert in measurement of streamflow.

U.S.G.S. (variously dated). National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 9, chaps. A1-A9.
http://water.usgs.gov/owq/FieldManual/ [Not available in paper; chapters available on-line.]

Source, type, and purpose: The USGS National Field Manual (NFM) is a compilation of science-based methods for collecting reproducible water quality data with minimum bias, published to encourage consistency in data collection methods.

Applicable river reach: All rivers and streams in the U.S.

Applicable big river characteristics: Flow rate and field conditions. These protocols enable the accurate and reproducible documentation of relationship between flow and water quality.

Summary of monitoring protocols: The NFM includes: preparations (Chapter A1), selection of equipment (Chapter A2), and cleaning of equipment (Chapter A3) for sampling, collection (Chapter A4) and processing (Chapter A5) of samples, field measurements (Chapter A6), biological indicators (Chapter A7), bottom-material samples (Chapter A8), and field safety (Chapter A9). Protocols have been kept up-to-date; all protocol chapters have been updated within the last decade. These protocols emphasize the use of science-based methods and quality assurance by field personnel. Consistent and comparable water-quality monitoring data are needed for all monitoring goals, including status and trends, compliance with standards, and emerging issues.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: Protocols apply to the full range of water resources within the MWMO.

Overall relevance: High. The NFM continues to be a popular template for monitoring protocols.

Yrjänä, T. (2003). Restoration of riverine habitat for fishes - analyses of changes in physical habitat conditions. Department of Process and Environmental Engineering doctoral thesis, University of Oulu, Finland, 39 pp. herkules.oulu.fi/isbn9514271173/isbn9514271173.pdf

Source, type, and purpose: University of Oulu, Finland doctoral dissertation to identify and test restoration measures for the most common physical habitat degradations in Finnish rivers.

Applicable river reach: Three oligotrophic and humic northern rivers, Iijoki, Oulujoki, and Siikajoki, which flow into Bothnian Bay, the northernmost gulf of the Baltic Sea.

Applicable big river characteristics: Channel type, flow rate, substrate properties, and lock-and-dams. Dredging and channel controls disrupt naturally-developed aquatic habitats.

Summary of monitoring protocols: Academically-proven (peer-reviewed and replicated) protocols for substrate quality, flow, and channel shape at stream transects. Data were used in a physical habitat simulation model to test restoration measures.

Summary of river conditions within MWMO: Not applicable.

Applicability of protocol to the MWMO: Similar to the Upper Mississippi River, the large regulated river Oulujoki consists of a series of river impoundments, and is completely harnessed for hydropower production. Model allowed for testing restoration measures before disrupting the river further. Recommended improvements include boulder dams, gravel ridges, and the excavation of narrow side channels. An increased hydro-physical habitat complexity means increased availability of suitable microhabitats for fish and their food resources.

Overall relevance: Low. Protocol may be useful for a study, but not for a monitoring program.

Zhang, J., H.T. Chen, Z.F. Zhang, S.M. Liu, and Y. Wu. (1999). Human impacts on the large world rivers: Would the Changjiang (Yangtze) River be an illustration? Global Biogeochemical Cycles 13:1099-1105.

Source, type, and purpose: Academic journal article to assessing the status of nutrient concentrations in the Changjiang River and its tributaries.

Applicable river reach: Changjiang (Yangtze) River.

Applicable big river characteristics: Tributaries, suspended sediments, and lock-and-dams. Human perturbations reduce the water and soil conservation ability of watersheds, resulting in siltation of riverine impoundments and channels, thereby reducing flood capacity.

Summary of monitoring protocols: Academically-proven (peer-reviewed and replicated) protocols for longitudinal river water quality surveys.

Summary of river conditions within MWMO or relevant results: This paper summarizes the results of a 4000-km longitudinal sampling cruise on the Yangtze River, plus 15 major tributaries, six months prior to closure of the Three Gorges Dam (TGD). Elevated nutrient concentrations in the mid-section of the Yangtze above TGD appear to be from point and nonpoint source loading from anthropogenic perturbations. Even though large tributaries in the middle and lower reaches of the basin are diluting the nutrient concentrations within the Yangtze River, nutrient loading near its mouth has nearly doubled in the last 10-20 years. Agricultural and population growth pressures are expected to push these loads higher. Reductions in sediment transport due to the TGD and increased nutrient loads are both expected to have detrimental effects on the coastal ecology.

Applicability of protocol to the MWMO: Differs from the MWMO, in that dams on Upper Mississippi River have been in place for nearly 100 years. Similar to the MWMO, in that current sedimentation problems are due to anthropogenic perturbations within the contributing land area.

Overall relevance: Moderate. Similar issues as those faced by the Mississippi.

ZumBerge, J.R., Lee, K.E., and Goldstein, R.M. (2003). Relation of periphyton and benthic invertebrate communities to environmental factors and land use at selected sites in part of the Upper Mississippi River Basin, 1996-1998. U.S. Geological Survey Water Resources Investigations Report 03-4121, 40pp. [PAPER COPY ONLY]

Source, type, and purpose: USGS report to characterize periphyton and benthic invertebrate communities in part of the Upper Mississippi River basin.

Applicable river reach: Twelve stream and river sites in the Upper Mississippi River basin, including a site on Shingle Creek and sites on the Mississippi River at Royalton, Anoka, and Hastings, and Red Wing.

Applicable big river characteristics: Substrate properties, suspended sediment, nutrients, and land use of contributing areas. The abundance of aquatic organisms is dependent on nutrient and sediment loads contributed by adjacent land areas.

Summary of monitoring protocols: USGS protocol for periphyton and invertebrate density and diversity. Site selection was stratified between drainage size, land use, and surficial geology. Indices such as diversity and richness did not perform as expected for small streams. Often the most disturbed streams had the highest values in the basin. Abundance, bio-volume and relative abundance seemed to be more meaningful measures than diversity indices.

Summary of river conditions within MWMO: In small streams, periphyton density increased in relation to nutrients. In large rivers, periphyton density was highest downstream, but diatom relative abundance decreased downstream as blue-green algae increased. In the Mississippi River, benthic invertebrate diversity and taxa richness decreased downstream.

Applicability of protocol to the MWMO: Study area included the Mississippi River through the Twin Cities Metropolitan Area, including the MWMO area. With suggested modifications, protocol is appropriate for assessment of aquatic organisms in this area.

Overall relevance: Low. Assuming the MWMO is not planning on biological monitoring.

ZumBerge, J.R., Perry, J.A., and Lee, K.E. (2003). Influence of local riparian cover and watershed runoff potential on invertebrate communities in agricultural streams in the Minnesota River Basin. U.S. Geological Survey Water Resources Investigations Report 03-4068, 13pp. http://pubs.usgs.gov/wri/wri034068/

Source, type, and purpose: USGS report to determine whether local riparian cover and watershed runoff potential affect invertebrate community composition.

Applicable river reach: 23 streams in the middle and lower Minnesota River basin.

Applicable big river characteristics: Elevation, riparian vegetation and land use of contributing area. Riparian cover and soil properties influence the movement of precipitation, soil, and associated contaminants into streams. Wooded riparian vegetation impedes surface runoff and stabilizes stream banks, thereby reducing the delivery of sediment into streams. Monitoring strategy should account for the influence of upland areas on macroinvertebrate distributions.

Summary of monitoring protocols: USGS selection of underwater woody debris sites and collection of macroinvertebrates.

Summary of river conditions within MWMO: Invertebrate community measures indicate greater degradation at the open riparian cover, high runoff potential sites and less degradation at the wooded riparian cover, low runoff potential sites. In addition, differences between streams with wooded riparian cover and sites with open riparian cover were greater in watersheds with high runoff potential. This study indicates that wooded riparian cover may be effective in maintaining stream biotic integrity in watersheds dominated by agricultural land use.

Applicability of protocol to the MWMO: The MWMO area has a smaller proportion of agricultural land use than the study streams, but protocol is relevant with respect to the higher runoff potential and modified riparian vegetation of urban areas.

Overall relevance: Moderate. Assuming the MWMO is not planning on biological monitoring.

Reference Tables

Table 1. References Addressing River Characteristics and Relative Importance of Reference

Big River Characteristic		Hydraulic Mixing			Hydraulic Time of Travel			Pollutant Mixing and Time of Travel		
		L	M	H	L	M	H	L	M	H
Physical: Discharge, volume, stage, and channel morphology	Precipitation (water/snow)								Ayers et al. (1985), Payne et al. (1982), Stark (1997)	Brown (1984)
	Elevation								Ayers et al. (1985), ZumBerge, Perry, and Lee (2003)	Lubinski (2004)
	Flow Rate	Johnson and Stefan (1987), Somlyody (1977)		Stefan (1982), Stefan et al. (1984), Taylor et al. (1985)	Somlyody (1977)		Taylor et al. (1985), Jobson (2000)	Yrjänä (2003)	Stark (1997), Stednick and Gilbert (1998)	Edwards and Glysson (1999), Lafrancois and Glase (2005), McDonald et al. (2002), MCES (2003), MPCA (2006), MPCA (2005), Morlock et al (2002), USGS TWRI Book 3 (var. dated), USGS TWRI Book 9 (var. dated)
	Seasonal and daily extremes of drought and flooding within the mainstem		Vandenberg et al. (2005)			Vandenberg et al. (2005)			Fallon and Chaplin (2001), Zhang et al. (1999)	Fallon and McNellis (2000)
	Tributaries		Putz and Smith (2001)					Andrews et al (1996), Lee and Anderson (1998), McNellis et al. (2001)	MetC (2005), MDA (2006), MPCA (2004), MPCA (2003), Payne et al. (1982), Stednick and Gilbert (1998), Zhang et al. (1999)	Engstrom and Almendinger (1998), Gilliom et al. (1995), Kloiber (2004), Kroening (1998), Lubinski (2004), Magdalene et al. (2007), McDonald et al. (2002), MCES (2003), MPCA (2006), MPCA (2005), Oakley et al. (2003), Stevens and Olsen (2004), Stark et al. (1999)
	Groundwater discharges							Andrews (1996), Andrews et al (1995), Andrews et al (1996), Fong	Capel et al. (1998), Hansen (1998)	Gilliom et al. (1995), Lafrancois and Glase (2005), Stark et al. (1999)
	River channel type/geometry	Boxall and Guymer (2003), Demetracopoulos (1994), Lee (1995), Rathbun and Rostad (2004)	Baek et al. (2006),Caplow et al. (2004), Lau (1985), Seo and Cheong (1998)			Caplow et al. (2004)		Yrjänä (2003)	Chick et al. (2005), Goldstein et al. (1999), Holland (1986), Kloiber (2003)	Soballe and Fischer (2004), Talmadge et al. (2000), USACE (1995), USGS TWRI Book 3 (var.
	River islands	Rathbun and Rostad (2004)								
	Ice cover, flows, and blockages			Lau (1985), Lau and Krishnappan (1981), Stefan et al. (1976)						
	Wind		Stefan (1982), Thene and Wang (2002), Voigt and Kostic (1998)	Stefan et al. (1976)						
	Dead zones	Beltaos and Arora (1988), Hunt (2006), Singh and Beck (2003),			Beltaos and Arora (1988), Singh and Beck(2003)					
Chemical	Field conditions (T, SC, pH, DO)	Stefan and Gulliver (1978)		Stefan (1982), Stefan et al. (1976)				Andrews et al (1996), Mistry et al. (2004)	Ayers et al. (1985), Chick et al. (2005), Goldstein et al. (1999), MPCA (2003)	McDonald et al. (2002), Oakley et al. (2003), Stevens and Olsen (2004), USGS TWRI Book 9 (var. dated)
	Pollutant properties	Hibbs et al. (1999), Hibbs and Gulliver (1999a), Hibbs and Gulliver			Hibbs et al. (1999), Jobson (1996), Jobson (1997)			Fong (2000), Lee and Anderson (1998), McNellis et al. (2001)	Fallon (2000), Kroening et al. (2000)	Lafrancois and Glase (2005), MDH (2001), Stark et al. (1999)
	Substrate properties							Yrjänä (2003), ZumBerge, Lee, and Goldstein (2003)	Angradi et al (2006), Chick et al. (2005), Fallon (2000), Goldstein et al. (1999), Holland (1986), James (2006), Shelton and Capel (1994)	Edwards and Glysson (1999), Flotemersch et al. (2006), Talmadge et al. (2000), USACE (1995), USEPA (2000)
	Suspended sediment							Mistry et al. (2004), ZumBerge, Lee, and Goldstein (2003)	Angradi et al (2006), Ayers et al. (1985), James (2006), MPCA (2004), MPCA (2003), Zhang et al. (1999)	Edwards and Glysson (1999), Engstrom and Almendinger (1998), MPCA (2006), MPCA (2005), Morlock et al (2002), USACE (1995)
	Nutrient cycling							MPCA (2003), Mistry et al. (2004), ZumBerge, Lee, and Goldstein (2003)	Ayers et al. (1985), Goldstein et al. (1999), Hanson (1998), James (2006), Johnson and Zelt (2005), MPCA (2004)	Engstrom and Almendinger (1998), Flotemersch et al. (2006), Kroening (1998), Magdalene et al. (2007), MDH (2001), MPCA (2006), MPCA (2005), Stevens and Olsen (2004)
Biological	Riparian vegetation								Angradi et al (2006), Chick et al. (2005), Goldstein et al. (1999), Johnson and Zelt (2005), Kloiber (2003), ZumBerge, Perry, and Lee (2003)	Lafrancois and Glase (2005), Talmadge et al. (2000)
	Primary productivity								Johnson and Zelt (2005)	Soballe and Fischer (2004)
Anthropogenic	Stormwater outfalls/pollutant point sources			Lau and Krishnappan (1981)				MPCA (2003)	Ayers et al. (1985), Kroening et al. (2000), Ledder (2003), Payne et al. (1982)	
	Private and industrial outfalls	Stefan and Gulliver (1978)						Lee and Anderson (1998)	Kroening et al. (2000)	
	Wastewater treatment plants		Metropolitan Council (2005), Vandenberg et al. (2005), Voigt and Kostic (1998)	Stefan (1982)				MPCA (2003)	Ledder (2003), MetC (2005)	Kloiber (2004)
	Land use of contributing area							Andrews et al (1996), Fong (2000), McNellis et al. (2001), ZumBerge, Lee, and Goldstein (2003)	Fallon (2000), Fallon and Chaplin (2001), Hanson (1998), Kloiber (2003), Kroening et al. (2000), Ledder (2003), MetC (2005), MDA (2006), Shelton and Capel (1994), Stark (1997), ZumBerge, Perry, and Lee (2003)	Brown (1984), Engstrom and Almendinger (1998), Fallon and McNellis (2000), Gilliom et al. (1995), Kloiber (2004), Kroening (1998), Lubinski (2004), Magdalene et al. (2007), MCES (2003), MDH (2001), MPCA (2005), MPCA (2006), Soballe and Fischer (2004), Stark et al. (1999), Talmadge et al. (2000), USEPA (2000)
	Water appropriations								Kloiber (2003)	MDH (2001)
	Vessel traffic		Voigt and Kostic (1998)	Stefan (1982)					Holland (1986)	Lubinski (2004)
	Lock-and-dams	Caplow et al. (2004)	Pujol and Sanchez-Cabeza (2000)	Taylor et al. (1985)	Caplow et al. (2004)		Taylor et al. (1985)	Yrjänä (2003)	Goldstein et al. (1999), Stark (1997), Zhang et al. (1999)	Kloiber (2004), Lubinski (2004), Soballe and Fischer (2004), USACE (1995)
	Wing dams		Stefan (1982)							
	Bridge piers									USACE (1995)
	Weirs	Stefan and Johnson (1987), Beltaos (1982)			Beltaos (1982)					

Table 2. References Addressing Theoretical Components and Relative Importance of Reference

Theoretical Component		Hydraulic Mixing			Hydraulic Time of Travel		
		L	M	H	L	M	H
Theoretical components	Models	USACE (1997), US EPA (2006)	Thene and Wange (2002), Voigt and Kostic (1998)	US EPA (2002)			
	Equations	Beltaos and Arora (1988), Beltaos (1982), Boxall and Guymer (2003), Boyle and Spahr (1985), Carr and Rehmann (2007), Cheong and Seo (2003), Elhadi et al. (1984), Hibbs and Gulliver (1999a), Hibbs and Gulliver (1999b), Holley (1972, Hunt (2006), Veliskova (2002), Jobson (1996), Jobson (1997), Kahlig (1979), Luk et al. (1990), Seo and Cheong (2001), Stefan and Gulliver (1978), Swamee et al. (2000), Toprak et al. (2004), Yotsukura et al. (1970)	Baek et al. (2006), Caplow et al. (2004), Hibbs et al. (1999), Koussis (1998), Lau and Krishnappan (1981b), Pujol and Sanchez-Cabeza (2000), Rathbun and Rostad (2004), Seo and Baek (2004), Seo and Cheong (1998), Singh and Baek (2003), Stefan (1982), Stefan et al. (1976), Taylor et al. (1985), Teichmann et al. (2002),	Eheart et. al. (1974), Lau (1985), Lau and Krishnappan (1981a), Gulliver (2007), Jobson (1987), Met Council (planned), Putz and Smith (2001)	Baek et al. (2006), Beltaos and Arora (1988), Beltaos (1982), Boyle and Spahr (1985), Cheong and Seo (2003), Jobson (1996), Jobson (1997), Kahlig (1979), Luk et al. (1990), Seo and Cheong (2001), Swamee et al. (2000), Toprak et al. (2004), Yotsukura et al. (1970)	Caplow et al. (2004), Hibbs et al. (1999), Koussis (1998), Lau and Krishnappan (1981b), Pujol and Sanchez-Cabeza (2000), Seo and Baek (2004), Seo and Cheong (1998), Singh and Baek (2003), Taylor et al. (1985), Teichmann et al. (2002)	Gulliver (2007), Jobson (2000), Met Council (planned)
	Longitudinal Dispersion Coefficient	Beltaos (1982), Boyle and Spahr (1985), Carr and Rehmann (2007), Gulliver (2007), Holley (1972, Jobson (1996), Jobson (1997), Kahlig (1979), Swamee et al. (2000),Yotsukura (1970)	Arntson et al. (2004), Baek et al. (2006), Beltaos (1982), Caplow et al. (2004), Koussis (1998), Rathbun and Rostad (2004), Seo and Baek (2004), Seo and Cheong (1998), Singh and Baek (2003), Teichmann et al. (2002)	Taylor et al. (1985)	Baek et al. (2006), Beltaos (1982), Boyle and Spahr (1985), Gulliver (2007), Jobson (1996), Jobson (1997), Kahlig (1979), Swamee et al. (2000), Yotsukura (1970)	Arntson et al. (2004), Beltaos (1982), Caplow et al. (2004), Koussis (1998), Seo and Baek (2004), Seo and Cheong (1998), Singh and Baek (2003), Teichmann et al. (2002)	Taylor et al. (1985)
	Transverse Dispersion Coefficient	Beltaos and Arora (1988), Boxall and Guymer (2003), Demetracopoulos (1994), Holley (1972), Koltun et al. (2006), Luk et al. (1990), Somlyody (1977)	Baek et al. (2006), Lau and Krishnappan (1981b), Rathbun and Rostad (2004)	Eheart et. al. (1974), Putz and Smith (2001)	Baek et al. (2006), Beltaos and Arora (1988), Luk et al. (1990)	Lau and Krishnappan (1981b)	
	Field Tests	Boyle and Spahr (1985), Ho et al. (2002), Lee (1995), Stefan and Gulliver (1978), Moody (1993), Yotsukura (1970)	Boyle (1985), Clark (1996), Hibbs et al. (1998), Koltun et al. (2006)	Met Council (planned), Lau (1985)	Boyle and Spahr (1985), Ho et al. (2002), Lee (1995), Yotsukura (1970)	Boyle (1985), Clark (1996), Hibbs et al. (1998)	Met Council (planned)

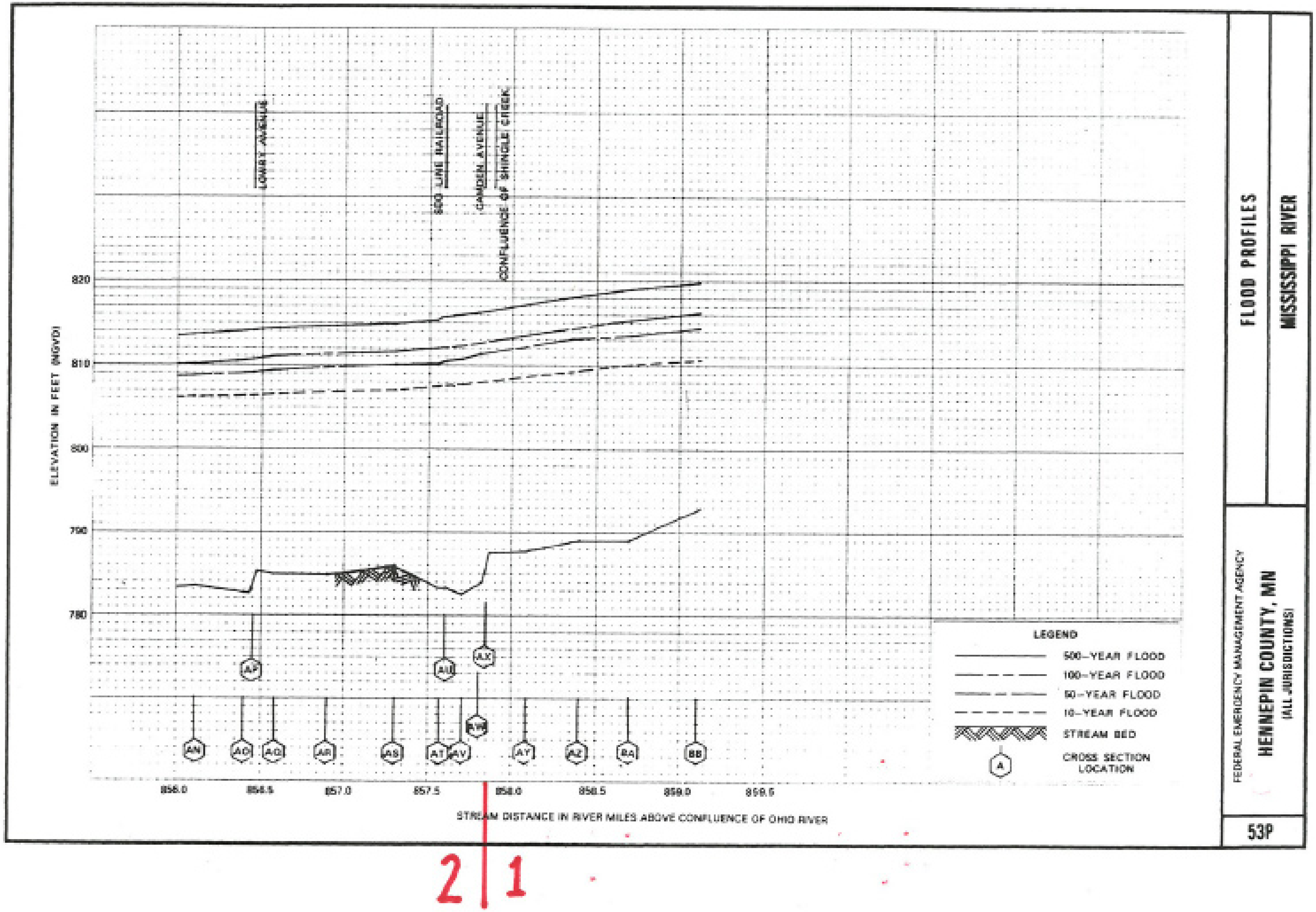
Table 3. References Addressing Studies of Local Conditions in the Portion of the Mississippi River that lies within MWMO

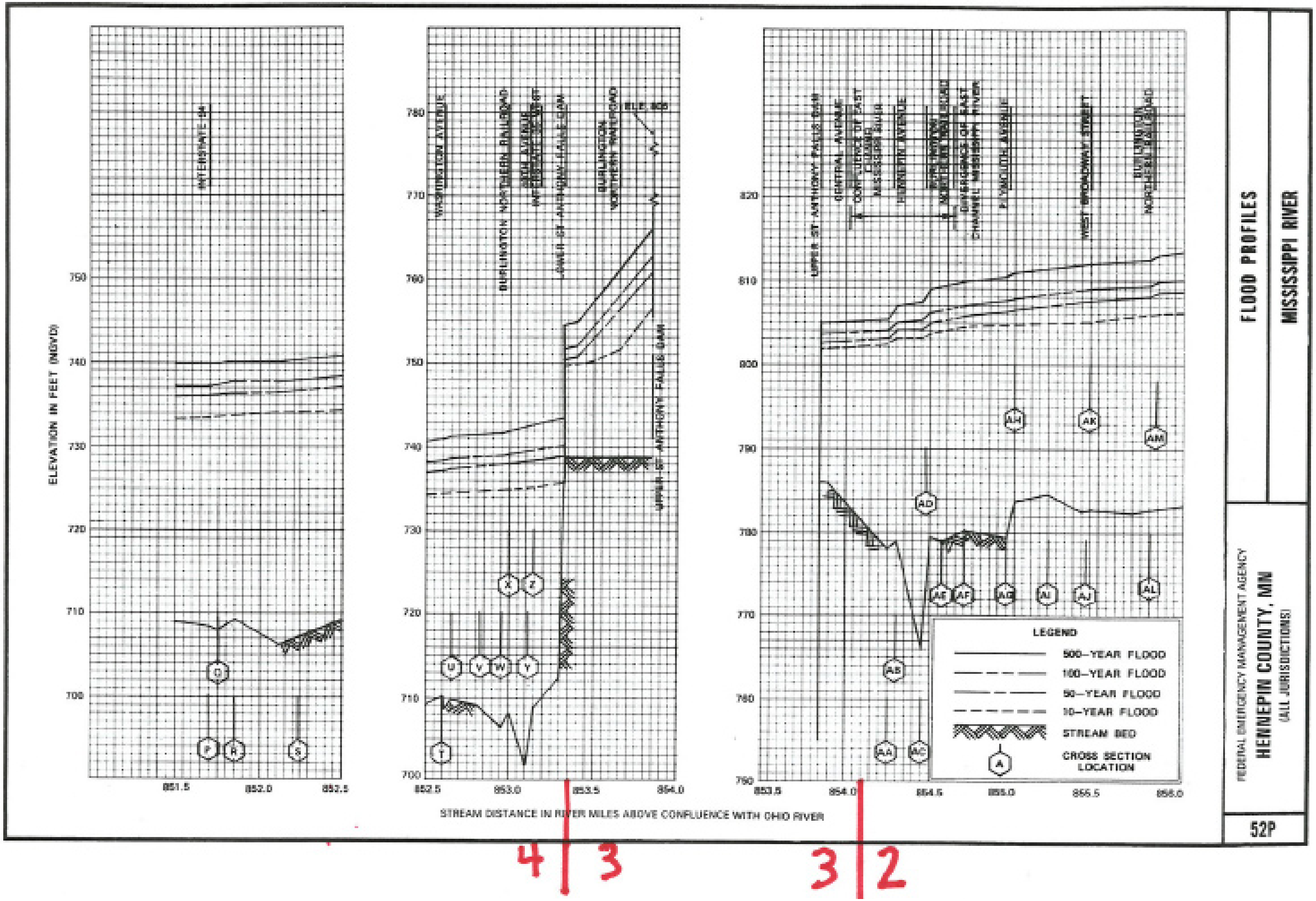
Type of Study	Hydraulic Mixing Studies	Monitoring Studies
Physical	Metropolitan Council (planned), MPCA (2006), Payne (1995), Schoenberg (1994), USACOE (planned), USACOE (2004), USACOE (2004a), USACOE (2004b), USACOE (2003a), USACOE (2003b), USACOE (2002), Winterstein (1982)	Andrews et al. (1996), Ayers et al. (1985), Capel et al. (1998), Fallon and Chaplin (2001), Hansen (1998), Lafrancois and Glase (2005), Lee and Anderson (1998), Kloiber (2004), Kroening (1998), McNellis et al. (2001), Talmadge et al. (2000)
Chemical	MPCA (2006), Winterstein (1982)	Andrews (1996), Andrews et al. (1995), Ayers et al. (1985), Chick et al. (2005), Fallon (2000), Goldstein et al. (1999), Kroening (1998), Magdalene et al. (2007), MDH (2001), MPCA (planned)
Biological	USACOE (planned), Winterstein (1982)	Chick et al. (2005), Goldstein et al. (1999), Kloiber (2003), ZumBerge, Perry, and Lee (2003)
Anthropogenic	City of Anoka (personal communication), City of Elk River (1982), City of St. Cloud (1988), Three Rivers Park District (2006), USACOE (planned), USACOE (2004a), USACOE (2004b), USACOE (2003a), USACOE (2003b),USACOE (2002), Winterstein (1982), Metropolitan Council (2005), Winterstein (1982)	Fallon (2000), Fallon and Chaplin (2001), Hanson (1998), Kloiber (2003), Kloiber (2004), Kroening et al. (2000), MetC (2005), Stark (1997), ZumBerge, Perry, and Lee (2003),

Contact List for Planned Studies

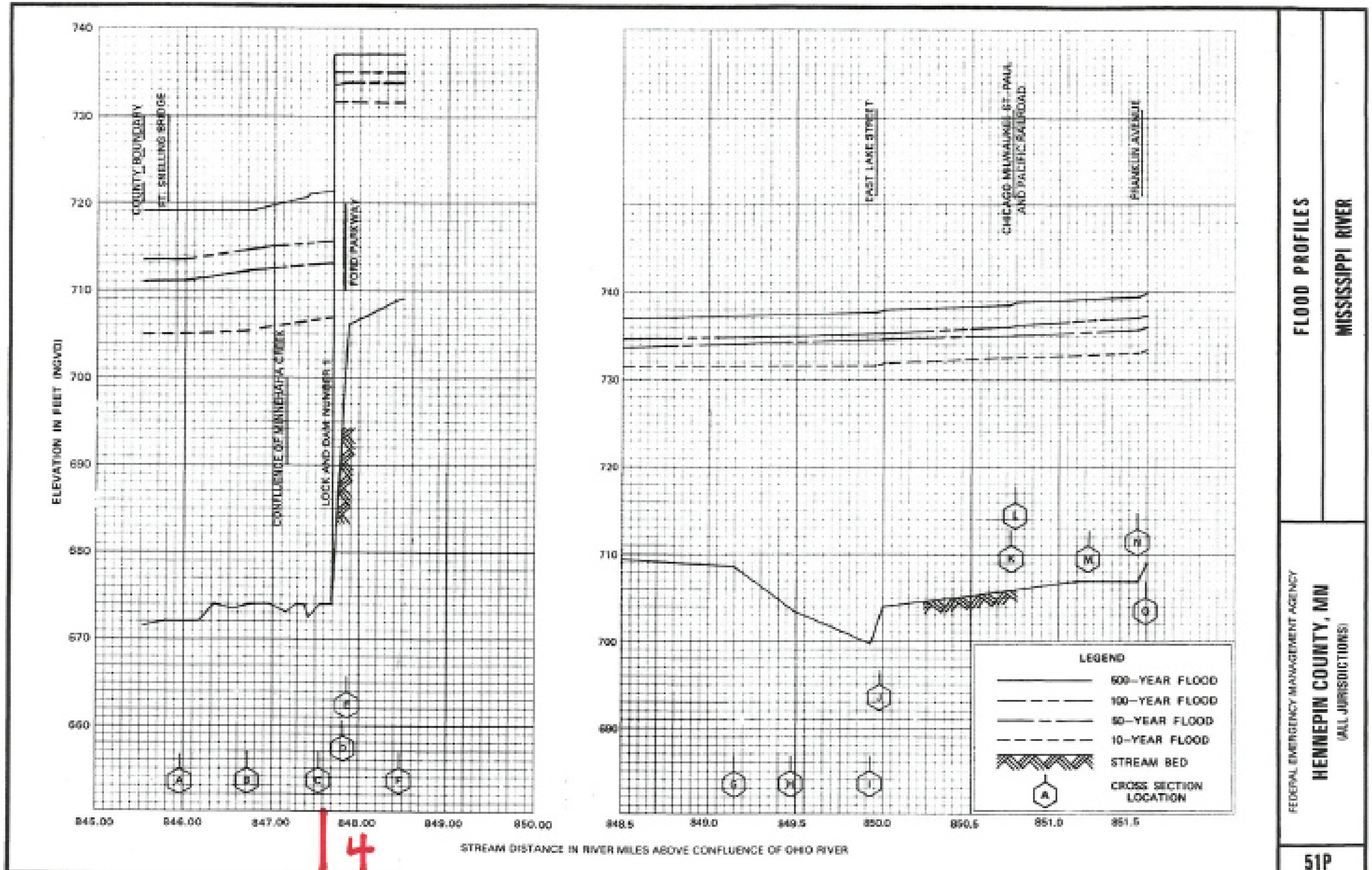
Name	Agency	phone	email	Reference in Annotated Bibliography
Russ Zastrow	City of Anoka	763-576-2782	russ@ci.anoka.mn.us	City of Anoka (personal communication- Hydraulic Mixing). Rum River Dam.
Cathy Larson	Metropolitan Council Environmental Services	651-602-1275	Cathy.Larson@metc.state.mn.us	Metropolitan Council (planned- Hydraulic Mixing). Lower Minnesota River Project.
Norm Senjem	Minnesota Pollution Control Agency	507-280-3592	Norman.Senjem@state.mn.us	Minnesota Pollution Control Agency (planned- Hydraulic Mixing). Part two of Lake Pepin TMDL Modeling Study, upstream of Lock & Dam 1.
Steve Clark	U.S. Army Corps of Engineers	651-290-5278	steven.j.clark@mvp02.usace.army.mil	U.S. Army Corps of Engineers (planned- Hydraulic Mixing). Reservoir Operating Plan Evaluation (ROPE) Study for Mississippi Headwaters.
Craig Affeldt	Minnesota Pollution Control Agency	651-296-6062	Craig.Affeldt@state.mn.us	Minnesota Pollution Control Agency (planned- Monitoring Protocols). Major watershed outlet monitoring protocol.

Appendix B. Flood Insurance Study Longitudinal Profile


LOWRY AVENUE
SOO LINE RAILROAD
CAMDEN AVENUE
CONFLUENCE OF SHINGLE CREEK
ELEVATION IN FEET (NGVD)
820
810
800
790
780
AN
AO
AQ
AP
AR
AS
AT
AU
AV
AW
AX
AY
AZ
BA
BB
856.0
856.5
857.0
857.5
858.0
858.5
859.0
859.5
STREAM DISTANCE IN RIVER MILES ABOVE CONFLUENCE OF OHIO RIVER
LEGEND
500–YEAR FLOOD
100–YEAR FLOOD
50–YEAR FLOOD
10–YEAR FLOOD
STREAM BED
CROSS SECTION LOCATION
FLOOD PROFILES
MISSISSIPPI RIVER
FEDERAL EMERGENCY MANAGEMENT AGENCY
HENNEPIN COUNTY, MN
(ALL JURISDICTIONS)
53P
2
1



ELEVATION IN FEET (NGVD)
STREAM DISTANCE IN RIVER MILES ABOVE CONFLUENCE WITH OHIO RIVER
INTERSTATE 94
WASHINGTON AVENUE
BURLINGTON NORTHERN RAILROAD
LOWER ST ANTHONY FALLS DAM
BURLINGTON NORTHERN RAILROAD
ELE. 805
UPPER ST. ANTHONY FALLS DAM
CENTRAL AVENUE
HENNEPIN AVENUE
PLYMOUTH AVENUE
WEST BROADWAY STREET
BURLINGTON NORTHERN RAILROAD
LEGEND
500–YEAR FLOOD
100–YEAR FLOOD
50–YEAR FLOOD
10–YEAR FLOOD
STREAM BED
CROSS SECTION LOCATION
FLOOD PROFILES
MISSISSIPPI RIVER
FEDERAL EMERGENCY MANAGEMENT AGENCY
HENNEPIN COUNTY, MN
(ALL JURISDICTIONS)
52P
4
3
3
2

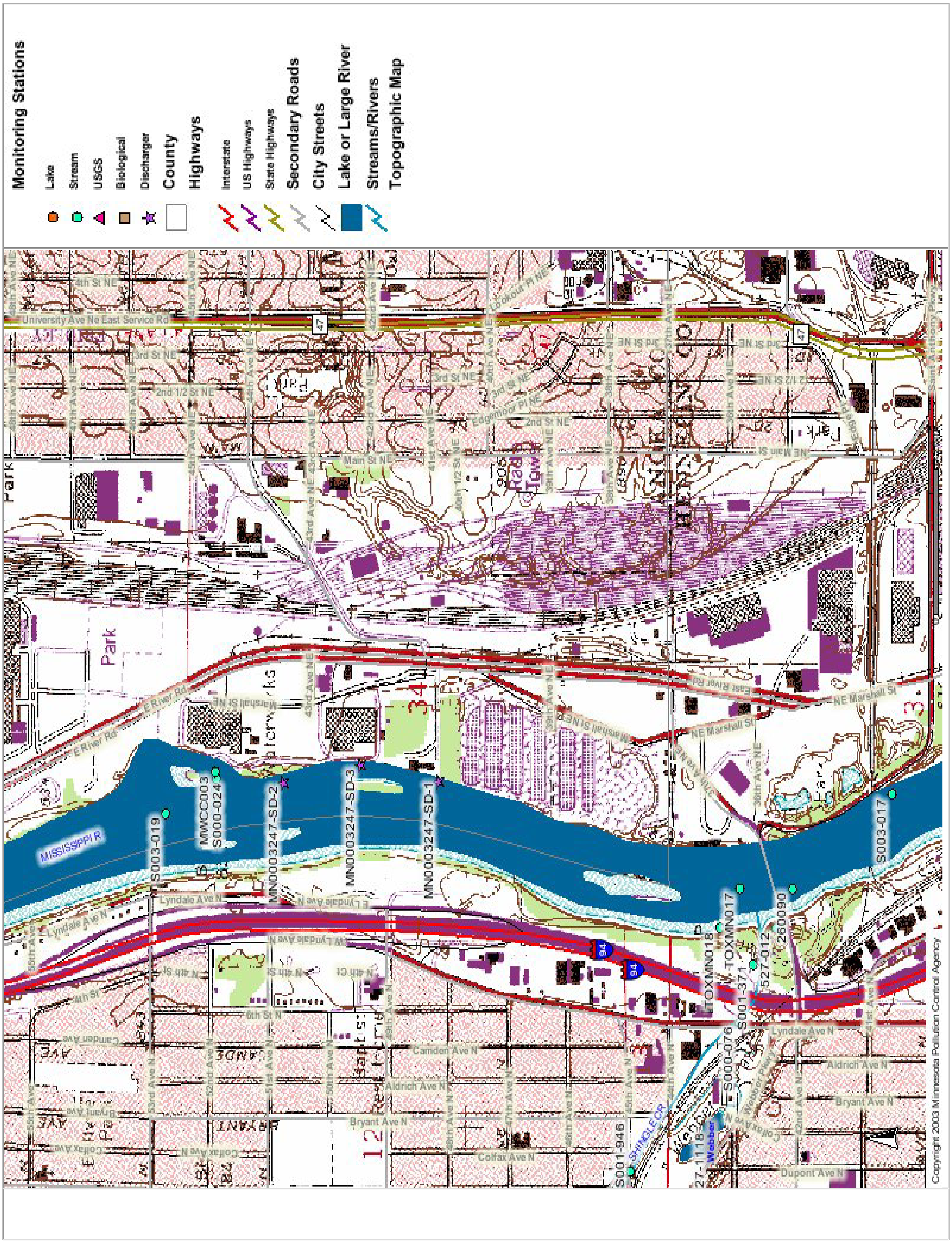


ELEVATION IN FEET (NGVD)
COUNTY BOUNDARY
FT. SNELLING BRIDGE
CONFLUENCE OF MINNEHAHA CREEK
LOCK AND DAM NUMBER 1
FORD PARKWAY
EAST LAKE STREET
CHICAGO MILWAUKEE ST. PAUL AND PACIFIC RAILROAD
FRANKLIN AVENUE
LEGEND
500-YEAR FLOOD
100-YEAR FLOOD
50-YEAR FLOOD
10-YEAR FLOOD
STREAM BED
CROSS SECTION LOCATION
STREAM DISTANCE IN RIVER MILES ABOVE CONFLUENCE OF OHIO RIVER
14
FLOOD PROFILES
MISSISSIPPI RIVER
FEDERAL EMERGENCY MANAGEMENT AGENCY
HENNEPIN COUNTY, MN
(ALL JURISDICTIONS)
51P

Appendix C. MWMO River Reaches Map

Figure C1: Base Map

Appendix D. NPDES Permit Location Maps



Monitoring Stations
Lake
Stream
USGS
Biological
Discharger
County
Highways
Interstate
US Highways
State Highways
Secondary Roads
City Streets
Lake or Large River
Streams/Rivers
Topographic Map
MISSISSIPPI R
S003-019
MWCC003
S000-024
MN0003247-SD-2
MN0003247-SD-3
MN0003247-SD-1
S003-017
TOXMN018
TOXMN017
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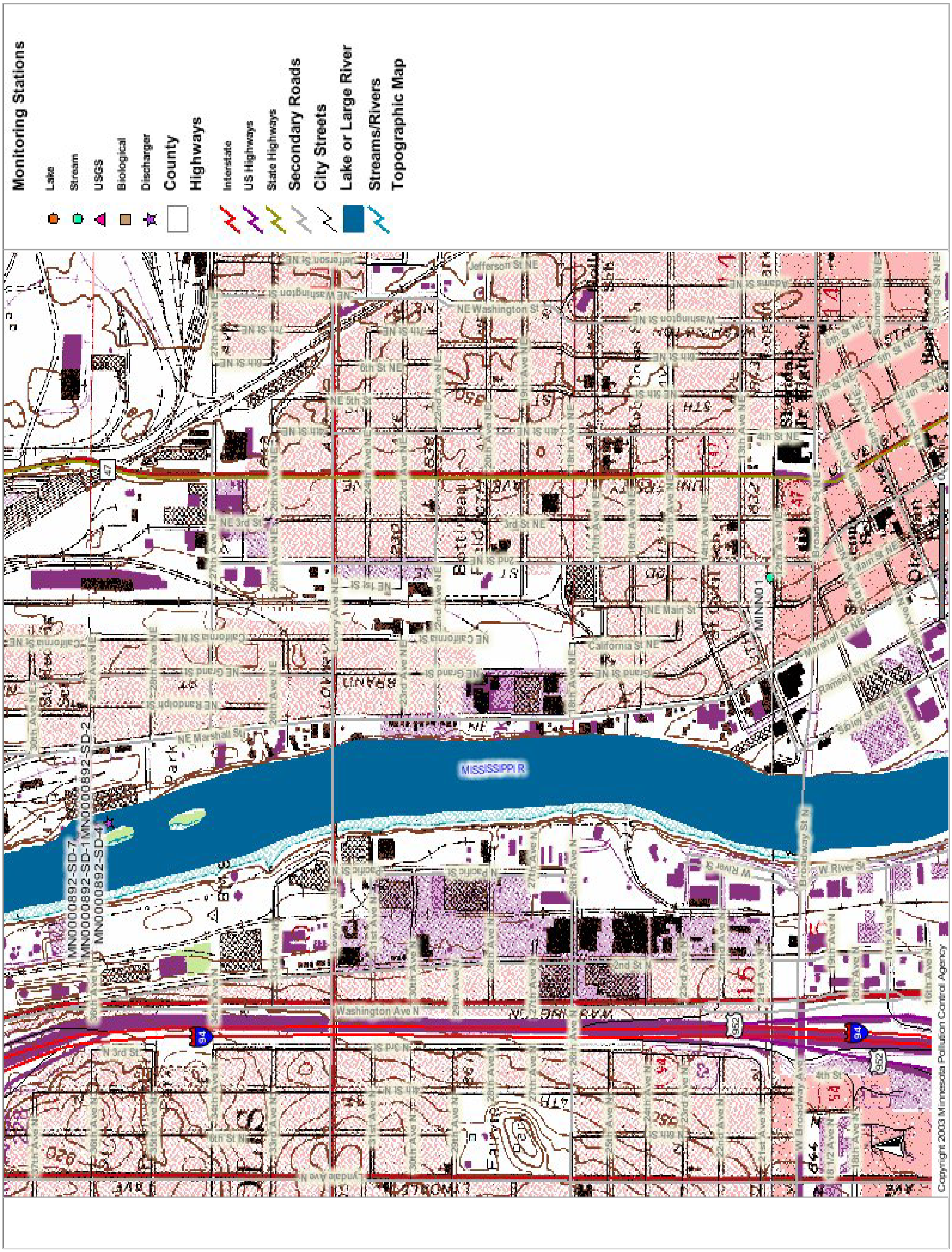
527-012
260090
S000-076
S001-946
SHINGLE CR
Copyright 2003 Minnesota Pollution Control Agency


Monitoring Stations
Lake
Stream
USGS
Biological
Discharger
County
Highways
Interstate
US Highways
State Highways
Secondary Roads
City Streets
Lake or Large River
Streams/Rivers
Topographic Map
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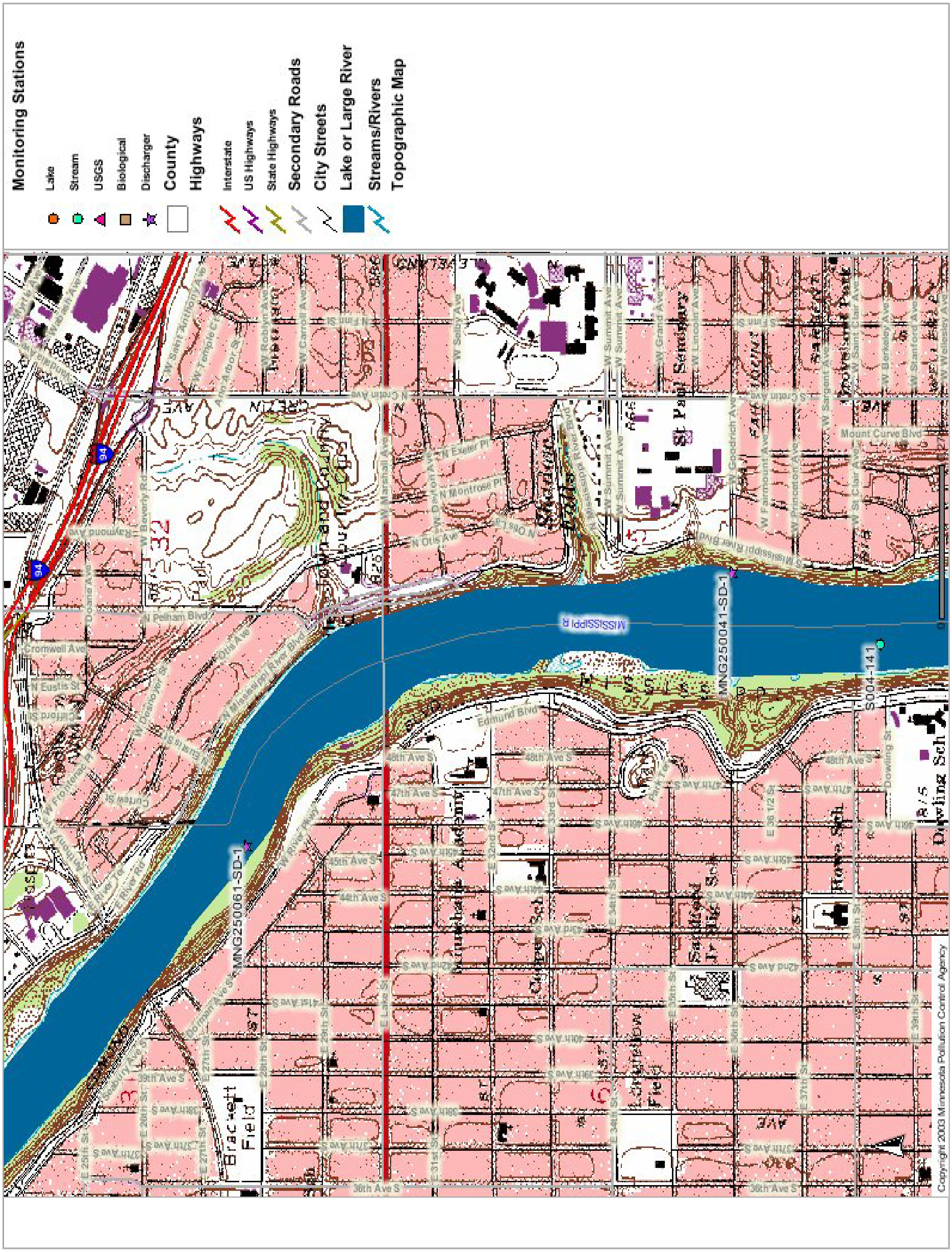
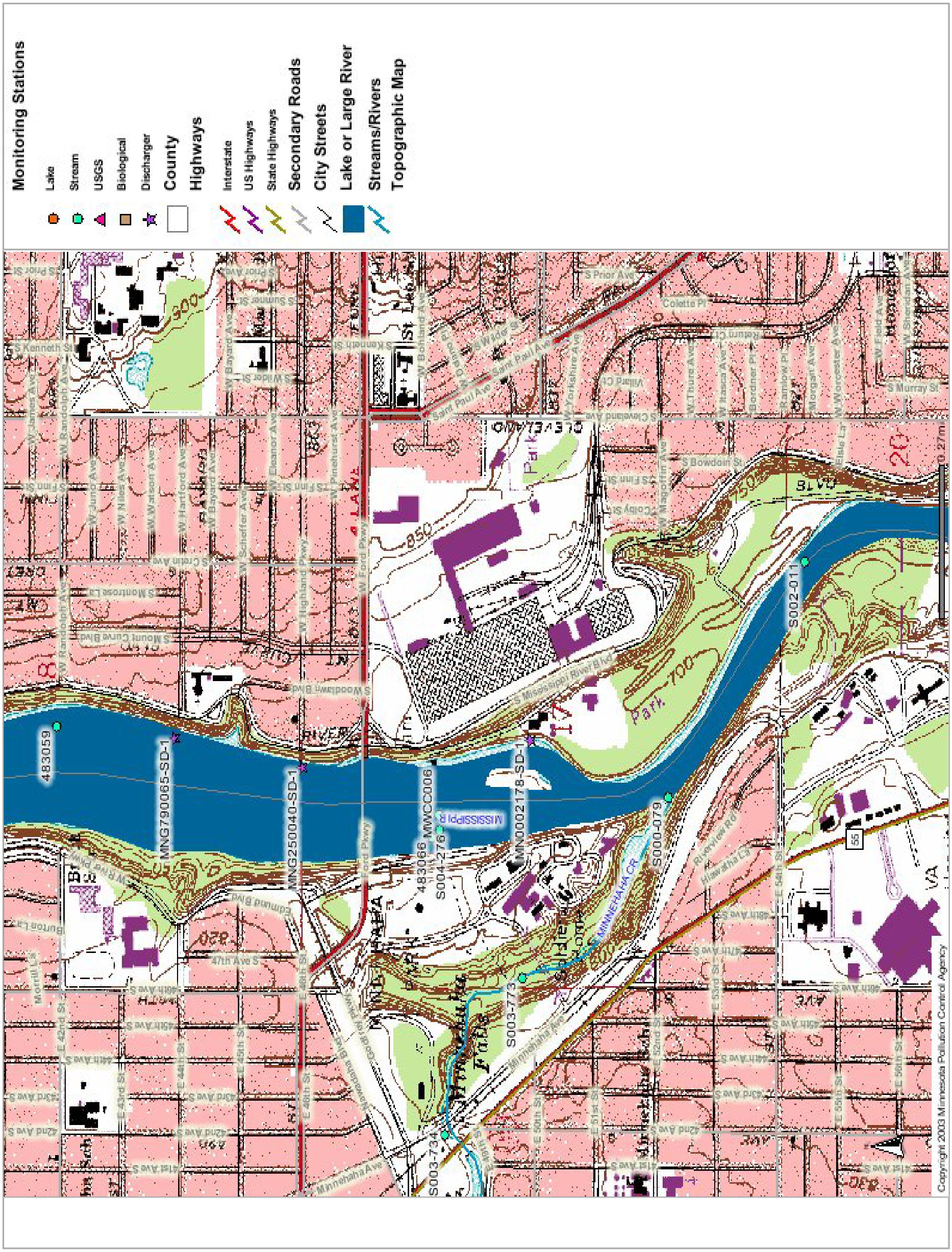
MN0000892-SD-1
MN0000892-SD-2
MN0000892-SD-4
MINN01
MISSISSIPPI R
Copyright 2003 Minnesota Pollution Control Agency


Monitoring Stations
Lake
Stream
USGS
Biological
Discharger
County
Highways
Interstate
US Highways
State Highways
Secondary Roads
City Streets
Lake or Large River
Streams/Rivers
Topographic Map
MNG250041-SD-1
MNG250061-SD-1
S004-141
MISSISSIPPI R
Copyright 2003 Minnesota Pollution Control Agency


Monitoring Stations
Lake
Stream
USGS
Biological
Discharger
County
Highways
Interstate
US Highways
State Highways
Secondary Roads
City Streets
Lake or Large River
Streams/Rivers
Topographic Map
483059
MNG790065-SD-1
MNG250040-SD-1
483066
MWCC008
S004-276
MN0002178-SD-1
S000-079
S002-011
S003-773
S003-734
MISSISSIPPI R
MINNEHAHA CR
Copyright 2003 Minnesota Pollution Control Agency

Appendix E. Mississippi River Bridge Crossings

Mississippi River bridge crossings and mid-river piers, pictured from downstream, listed by river mile location from upstream to downstream.

Note longitudinal changes in riparian vegetation, surrounding land use, and bank elevation.

Camden River Bridge (RM=857.8): Two mid-river piers

Canadian Pacific Camden Place Railroad Bridge (RM=857.6): Four mid-river piers

Lowry Avenue Bridge (RM=856.4): Four mid-river piers

NP-BN-SF Railroad Bridge (RM=855.8): Five mid-river piers

Broadway Avenue Bridge (RM=855.4): Three mid-river piers

Plymouth Avenue Bridge (RM=855.0): Three mid-river piers

BN-SF Railroad Bridge (RM=854.5): Three mid-river piers

Hennepin Avenue Bridge (RM=854.3): No mid-river piers

Third Avenue Bridge (RM=854.1): Six mid-river piers

Stone Arch Bridge (RM=853.6): Twelve mid-river piers

Interstate 35-W Bridge (RM=853.2, planned for Late 2008): No mid-river piers

10th Avenue Bridge (RM 853.1): One mid-river pier

Northern Pacific Bridge No. 9 (RM=853.0): Two mid-river piers

Washington Avenue Bridge (RM=852.6): One mid-river pier

Dartmouth (Interstate 94) Bridge (RM=851.7): Two mid-river piers

Franklin Avenue Bridge (RM=851.5): Two mid-river piers

Short Line Bridge (RM=850.7): Two mid-river piers

Lake Street Bridge (RM=849.9): One mid-river pier

Intercity (Ford Parkway) Bridge (RM=847.8): Two-mid-river piers