REGIONAL ASSESSMENT OF RIVER WATER QUALITY IN THE TWIN CITIES METROPOLITAN AREA 1976-2015

Minnesota, Mississippi, St. Croix Rivers

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June 2018

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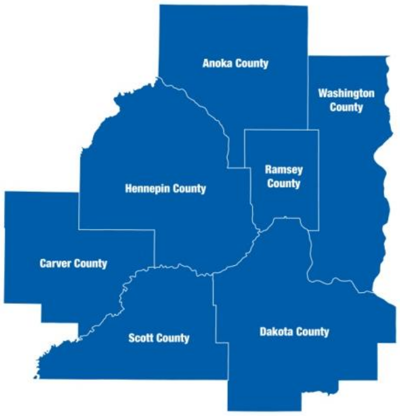

The Metropolitan Council is the regional planning organization for the seven-county Twin Cities area. The Council operates the regional bus and rail system, collects and treats wastewater, coordinates regional water resources, plans and helps fund regional parks, and administers federal funds that provide housing opportunities for low- and moderate-income individuals and families. The 17-member Council board is appointed by and serves at the pleasure of the governor.

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About This Report

This water quality assessment of the three major rivers of the Twin Cities metropolitan area – the Mississippi, the Minnesota, and the St. Croix – is a report of Metropolitan Council Environmental Services (MCES), a division of the Metropolitan Council. The Metropolitan Council is the regional policy-making body, planning agency, and provider of essential services for the metro area.
The Metropolitan Council's mission is to foster efficient and economic growth for a prosperous metropolitan region.

MCES provides wastewater services and integrated planning to ensure sustainable water quality and water supplies for the region. Additionally, MCES has established several monitoring programs to measure and assess the quality of regional surface waters, including rivers, streams, and lakes. The monitoring data constitute a valuable source of reliable, impartial, and timely information to support a comprehensive understanding and management of water resources in the region.

Focusing on the region's three major rivers, this report examines recent river water quality conditions and long-term trends in water quality parameters for select physical and chemical constituents that have been monitored at 10 river sites since 1976. It builds on previous river trend studies of the region by incorporating more recent years of data and using a newer trend model (QWTREND).

The results found in this report provide a base of technical information that can support sound decisions about water resources in the metro area – decisions by the Metropolitan Council, state agencies, watershed districts, conservation districts, and county and city governments.

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INTRODUCTION

The Twin Cities metropolitan area is a region of 3,000 square miles encompassing seven counties and 181 communities. The area developed around three major rivers: the Mississippi, Minnesota, and St. Croix (Figure 1). European settlement began in the 1820s near Fort Snelling, located at the confluence of the Minnesota and Mississippi rivers. Today, the population of the metro area is more than three million and projected to be 3.74 million by 2040 (Metropolitan Council, 2017).

History of Water Quality Issues

In the late 19th and early 20th centuries, urbanization and a growing population led to severely degraded water quality, caused especially by the direct discharge of untreated sanitary sewage into rivers and lakes. In the Mississippi River, the discharge of untreated sewage by the mid-1920s caused oxygen depletion, extremely high levels of bacteria, formation of floating mats of sewage, and the near destruction of fish populations (USEPA, 2000).

While increased mechanization and use of chemical fertilizers in the later 1900s expanded agricultural productivity, agricultural areas, especially within the Minnesota River Basin, contributed heavy loads of sediments, nutrients, and other contaminants to metro area waters. Engstrom et al. (2009) found that the Minnesota River contributed nearly 90% of the sediment load and 50% to 85% of the nonpoint total phosphorus load to Lake Pepin, a natural impoundment of the Mississippi River downstream of the metro area.

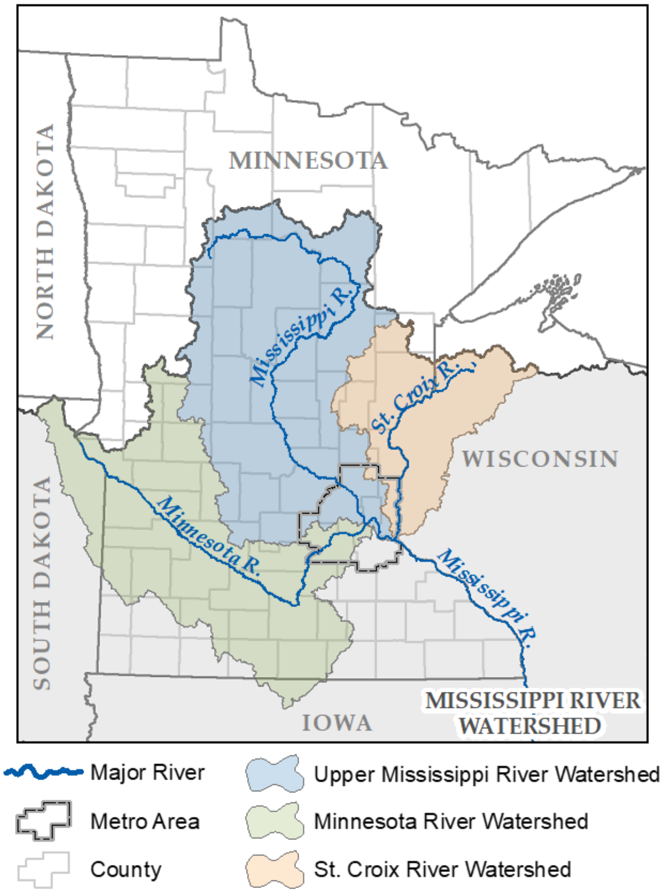
To manage the impact of population growth on regional water quality and to protect public health, the Metropolitan Waste Control Commission (now part of the Metropolitan Council), initiated a long-term effort to protect and improve regional water quality. The effort began in 1938 when the Metropolitan Wastewater Treatment Plant (WWTP) was built in direct response to the acute public health problem caused by the deterioration of water quality in the Mississippi River. Today, Metropolitan Council Environmental Services (MCES), a division of the Metropolitan Council, operates seven advanced WWTPs and one regional reclamation facility in the metro area.

These progressively intensive wastewater treatment practices, the separation of sanitary and storm sewers during the 1985-1995 period, and the basin-wide application of urban and agricultural best management practices (BMPs), have contributed to significant improvements in regional river water quality in recent decades. Evidence of this progress is seen in increased water clarity, growing numbers of bald eagles, a recovered world-class walleye population, and annual mayfly hatches.

MCES has a river monitoring program spanning more than 150 river miles in the metro area, covering the Mississippi, Minnesota, and St. Croix Rivers. These rivers are monitored for a variety of physical, chemical, and biological parameters, to document long-term changes in water quality and characterize biological communities.

Long-term water quality trends in the Mississippi, Minnesota, and St. Croix rivers within the metro area are of great interest to the Metropolitan Council, governmental agencies, and the public, because changes in river water quality affect public health, aquatic biological communities such as fish and insects, and the ability of people to swim, fish, and enjoy recreation in the rivers. Analysis of trends can indicate how statewide and regional pollution control programs benefit regional river water quality.

Figure 1. Major Rivers and Watersheds of the Twin Cities Metropolitan Area



Previous Studies

During the past few decades, several studies have evaluated water quality trends in regional rivers. Some studies graphically compared annual median concentrations of select physical and chemical parameters (Kroening and Andrews, 1997; Lafrancois et al., 2013; Larson et al., 1976; USEPA, 2000). This approach is helpful to understand general patterns in river water quality.

Other studies used non-parametric statistical methods, for example, the seasonal Kendall Tau test, to detect monotonic trends in water quality (MCES, 2004; Lafrancois et al., 2013). The seasonal Kendall Tau method is a well-tested and widely used trend analysis technique. However, as indicated by Lafrancois et al. (2013), the non-parametric statistical methods are limited because they focus on hypothesis testing rather than a description of change, and they are valid under several assumptions such as linear patterns of change, constant seasonal patterns and flow versus concentration relationships. Lafrancois et al. (2013) recommended further evaluation using more advanced trend analysis techniques, which is done in this study.

Importance of Flow-Adjusted Trends

Trends in water quality can be affected by both natural processes (such as precipitation, river flow and geologic conditions), and human activities (such as agriculture, urban development, implementation of BMPs, and wastewater treatment technology). Flow and natural variations have a considerable influence on the water quality of a river. High flows are generally associated with an increased delivery of pollutants from the watershed, while low flows can amplify point sources of pollution, when less water is available to provide a dilution effect. To assess changes in water quality resulting from human activity, it is important to consider the flow-adjusted trends, which are the changes in water quality over time with removed effects of flow variation on concentrations (Sprague et al., 2006). On the other hand, the trends not adjusted for flow are the overall changes in water quality resulting from both natural and human factors. The flow-adjusted trends can then be used to identify emerging water quality problems and better understand how pollution reduction efforts and investments contribute to improvements in river water quality.

To analyze water quality trends based on flow-adjusted concentrations, the Metropolitan Council used the Quality of Water Trend (QWTREND) statistical model. The model was developed by the U.S. Geological Survey (USGS) (Vecchia, 2005). Compared to previous models, this approach has the potential to better describe the nature of long-term and non-monotonic trends in water quality and identify the changes caused by human activities (for example, changes in point source contributions and land uses, BMP implementation). Previously, the Minnesota Pollution Control Agency (MPCA) used QWTREND to study long-term trends for nitrate-nitrogen concentrations in Minnesota surface waters, including several metro area river sites (MPCA, 2014).

In this study, QWTREND was applied to select parameters measured at various locations along the three major metro area rivers to assess changes in water quality during the 1976-2015 period. The assessment identified water quality improvements that have occurred in response to regional pollution-reduction efforts, and it also identified emerging water quality concerns such as contamination of chloride from increased population and urban development. In addition to statistical analysis of water quality trends, annual and monthly median concentrations of water quality parameters were calculated to provide an analysis of recent water quality conditions and spatial variations in these rivers.

This study covers results from six monitoring sites on the Mississippi River, two on the Minnesota River and two sites on the St. Croix River. The locations of these sites make it possible to assess the quality of water entering and leaving the metro area, as well as water quality changes that occur as these rivers pass through the region.

Water Quality Parameters

In this study, 15 water quality parameters represent water quality conditions of the three rivers:

- River flow
- Dissolved oxygen (DO)
- 5-day biochemical oxygen demand (BOD_5)
- Water temperature
- pH
- Conductivity
- Total suspended solids (TSS)
- Total phosphorus (TP)
- Corrected chlorophyll-*a* (Chl-*a*)
- Total nitrogen (TN)
- Nitrate-nitrogen (NO_3)
- Ammonia-nitrogen (NH_3)
- Fecal coliform bacteria (FC)
- *Escherichia coli* bacteria (*E. coli*)
- Chloride (Cl)

These parameters were selected because they are often used to summarize river water quality and are related to important water quality concerns. All of them can impact (or are indicators of) water quality conditions that affect aquatic life and the ability to use the rivers for recreational activities, such as swimming, boating, and fishing. Many of these parameters have water quality standards that are meant to ensure that Minnesota waters are “fishable and swimmable”, as required by the federal Clean Water Act.

Nine of these parameters were selected for QWTREND analysis and to explore the water quality conditions in the rivers: BOD_5, TSS, TP, Chl-*a*, TN, NO_3, NH_3, FC, and Cl. They are related to major water quality concerns such as adequate oxygen, water clarity, eutrophication, algae blooms, bacterial contamination, and excessive salinity. Data for two parameters, DO and *E. coli*, did not meet the minimum requirements necessary for analysis with QWTREND. Details on the requirements for QWTREND are provided in “Study Methods.” The remaining parameters, flow, temperature, pH, and conductivity, were used to summarize basic conditions in the rivers but were considered too general to use QWTREND to address specific water quality concerns.

The results presented in this report are based on data provided by the MCES river monitoring program during the 1976-2015 period. The flow data used for this analysis include measurements at relevant river sites of the USGS and U.S. Army Corps of Engineers (USACE) from 1971 to 2015.

Focus of the Study

The purpose of this report is to assess the water quality of the Mississippi, Minnesota, and St. Croix rivers within the metro area. The specific report objectives are as follows:

- Characterize recent water quality conditions (2006-2015) and spatial changes along these rivers
- Analyze long-term water quality trends (1976-2015) in these rivers
- Discuss the factors contributing to observed water quality changes
- Identify current water quality issues and needs for improvement
- Provide recommendations for future water quality monitoring and data assessment
- Provide recommendations for future management actions that can improve and protect regional river water quality

STUDY AREA AND SCOPE

The water quality of the Mississippi, Minnesota, and St. Croix rivers entering the metro area is influenced by conditions in the upstream watersheds. In turn, the metro area impacts the water quality of the rivers as they move through the region. The three rivers are important resources locally and nationally for recreation, culture, habitat, and transportation of goods. Two national parks in the metro area, the Mississippi National River and Recreation Area and the St. Croix National Scenic Riverway, feature the rivers, as do many other state, regional, and local parks.

Additionally, approximately 50 cities along its length use the Mississippi River as a source of drinking water for millions of people (NPS, 2017), including Minneapolis and Saint Paul. Over a quarter of the water used in the metro area comes from surface water, specifically the Mississippi River (MCES, 2015). To protect the benefits provided by the regional rivers, it’s useful to consider the characteristics of their watersheds that may influence water quality. The characteristics discussed in this section include:

- Geography
- Metro area population
- Regional climate and weather
- Ecoregions and geology
- Land cover
- Current environmental conditions

Geography

River Geography

The Mississippi River is one of the world’s largest rivers, flowing over 2,300 miles through the center of the United States (Figure 2). The Mississippi River begins at Lake Itasca in northern Minnesota and enters the metro area at the border of Anoka and Hennepin counties near river mile 879 (river miles in this part of the Mississippi River are measured as the distance upstream from the confluence of the Mississippi and Ohio rivers near Cairo, Illinois). From there, it travels about 72 miles before exiting the metro area in Dakota County near river mile 807.

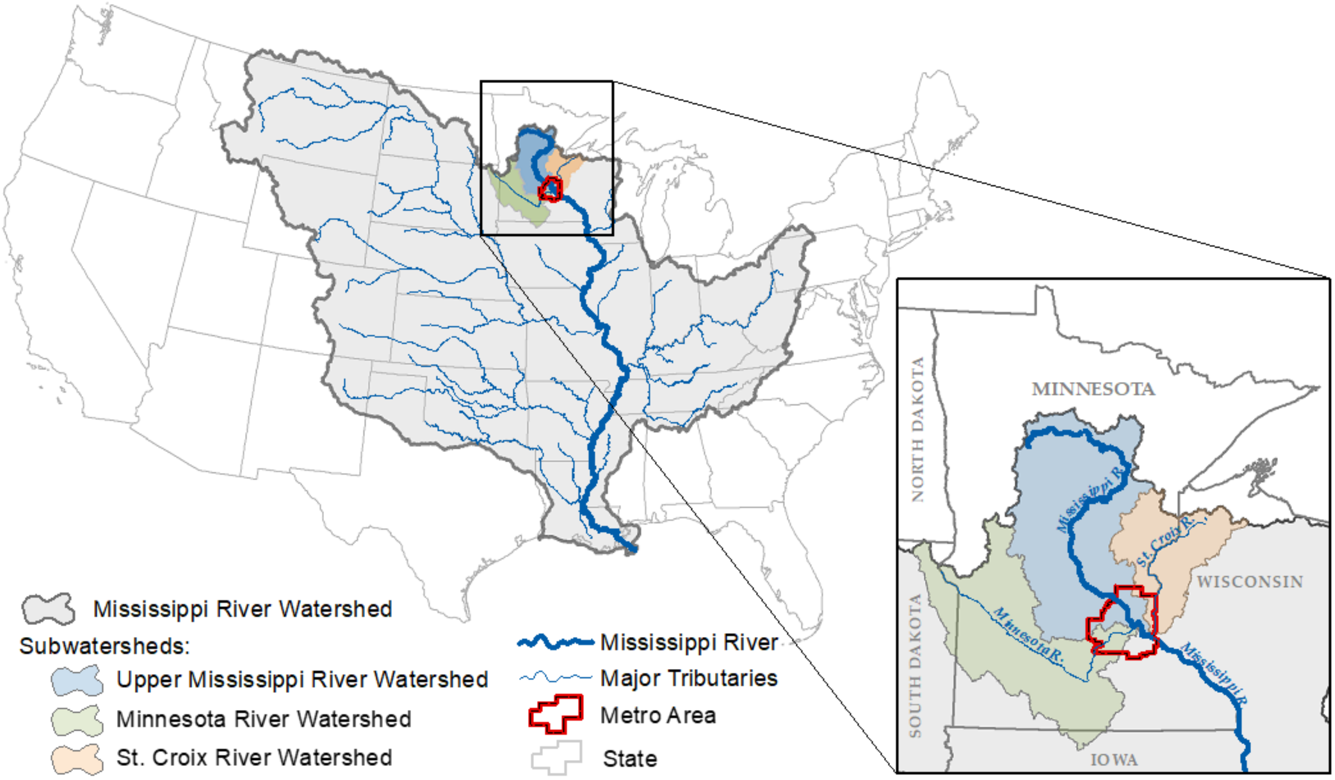
Downstream of the metro area, the Mississippi widens into Lake Pepin, near river mile 785.4, the largest natural lake on the river. The slower moving waters in Lake Pepin allow material to settle out of the river, and Lake Pepin is currently impaired for eutrophication (that is, excess nutrients) and TSS (MPCA, 2007; 2016a). The Mississippi continues south and ultimately drains into the Gulf of Mexico, where the pollutants transported from the river contribute to the oxygen-deficient “Dead Zone” (MPCA, 2013).

The Minnesota River is a 332-mile-long tributary of the Mississippi River, originating at Big Stone Lake near the South Dakota-Minnesota border. It travels eastward across southern Minnesota before entering the southwest corner of the metro area, forming the border of Carver and Scott counties, near river mile 66 (river miles of the Minnesota River are measured as the distance upstream of where the river ends at the Mississippi River). From there, it flows approximately 66 miles before entering the Mississippi River near historic Fort Snelling.

The St. Croix River is a tributary of the Mississippi River, spanning a total of 164 miles through Wisconsin and Minnesota. The river starts at Upper St. Croix Lake in northwestern Wisconsin near the city of Solon Springs. The river reaches the metro area from the northeast near river mile 43 (river miles of the St. Croix River are measured as the distance upstream of where the river ends at the Mississippi

River). It flows along the eastern border of Washington County in the metro area before entering the Mississippi River near Prescott, Wisconsin.

Figure 2. Entire Mississippi River Watershed



Watershed Geography

The full Mississippi River watershed is the fourth largest in the world and covers about 1.2 million square miles, about 40% of the lower 48 states (Figure 2). The metro area, with an area of roughly 3,000 square miles, lies entirely within the Mississippi River watershed.

Three subwatersheds of the Mississippi River watershed cover most of the metro area: the Upper Mississippi (defined within Minnesota and throughout this report as the Mississippi River upstream from the St. Croix River confluence at river mile 811), the Minnesota River, and the St. Croix River. The Upper Mississippi watershed covers 47% of the metro area; the Minnesota River watershed, 26%; the St. Croix River watershed, 11%. The remaining 16% of the metro area falls in the Lower Mississippi River watershed (defined within Minnesota and throughout this report as the Mississippi River watershed downstream from the St. Croix River confluence).

The Upper Mississippi River watershed covers about 21,100 square miles of Minnesota, 6.9% of which falls within the metro area. The Minnesota River watershed drains about 17,000 square miles, extending into parts of South Dakota and Iowa. About 4.5% of the Minnesota River watershed falls within the metro area. The watershed area of the St. Croix River lies in Minnesota and Wisconsin and covers about 7,760 square miles. About 4.4% of the St. Croix River watershed falls inside the metro area.

Metro Area Population

A growing population imposes additional stress on the region's rivers by introducing pollution levels that would not occur in more natural environments. This is the case in the metro area, which has undergone significant changes over time during past decades due to an increasing population and economic development. As shown in Figure 3, the population of the metro area grew substantially between 1970 and 2010, from approximately 1.87 million to 2.85 million people (U.S. Census Bureau, 2015). The Metropolitan Council estimates that the population will continue growing over the next three decades to nearly 3.74 million by 2040.

Regional Climate and Weather

Precipitation, snowfall, and temperature are elements of weather and climate that contribute to the amount and timing of runoff feeding into the region's rivers. These elements vary over time and between locations, causing natural variation in the amount of runoff and river flow by season and by year, thereby impacting the water quality of the river. In general, runoff into the rivers is highest during spring snowmelt and after storm events.

Minnesota has a continental climate, characterized by four distinct seasons with hot, often humid, summers and cold winters (Figure 4). Annual precipitation is generally lower in the northwest and increases moving southeast. Annual snowfall is similar across most of the state except in the northeast, which experiences higher snowfall due to moisture from Lake Superior. As expected, average annual temperatures are cooler in the north and increase moving south.

Figure 3. Metro Area Population Growth and Forecast by County, 1970-2040 (Metropolitan Council, 2018; U.S. Census Bureau, 2015)

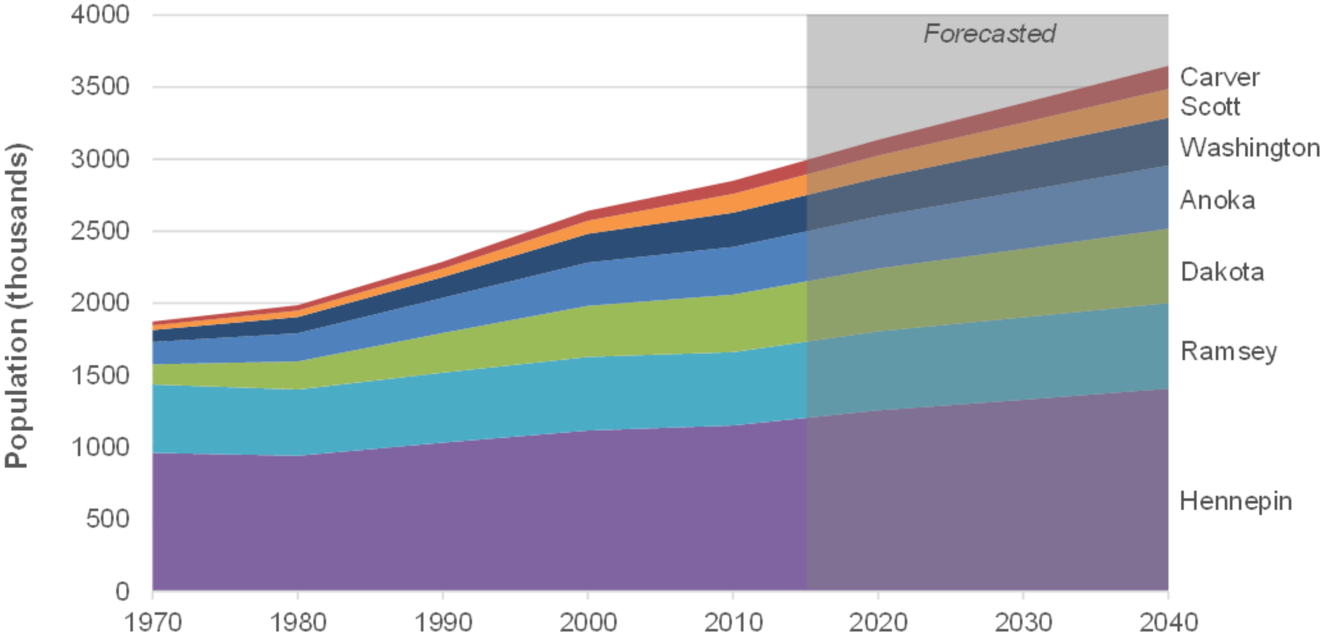
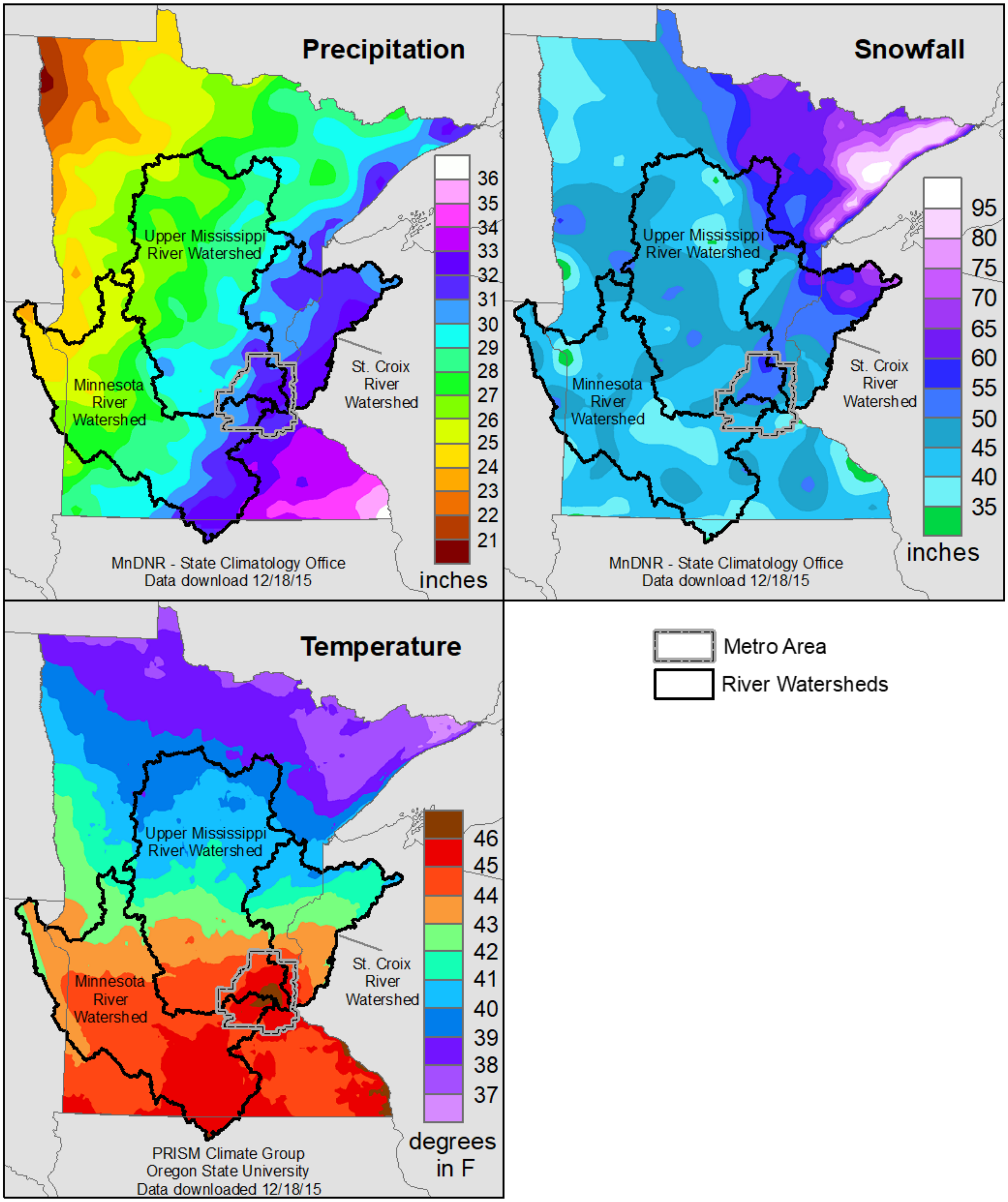
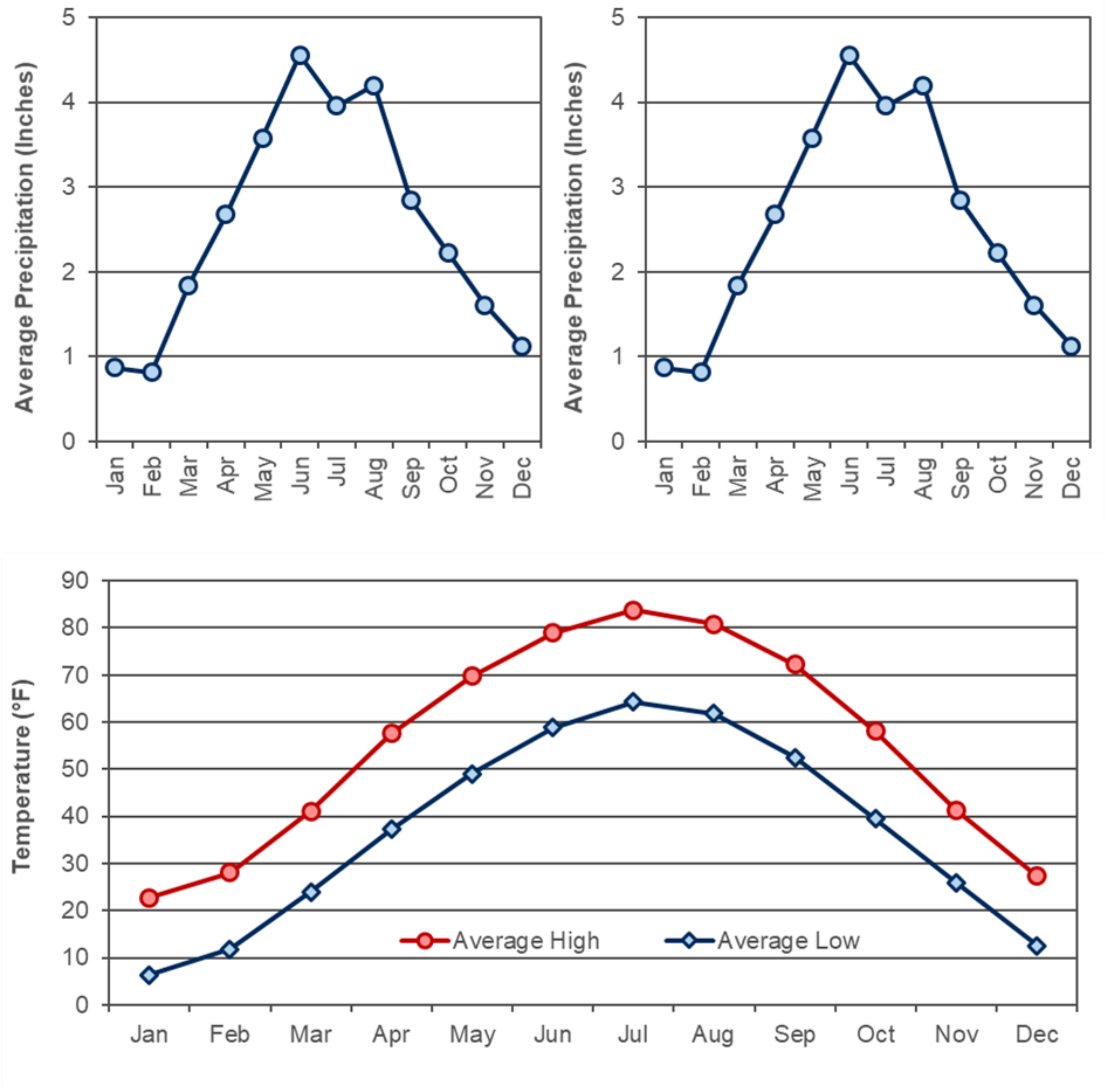


Figure 4. 1980-2010 Minnesota Climate Normals of Precipitation (MnDNR, 2012a), Snowfall (MnDNR, 2012b), and Temperature (PRISM, 2015)



From 1976 to 2015, the weather monitoring station at the Minneapolis-Saint Paul International Airport (MSP), located in the core of the metro area, recorded an average precipitation of about 30 inches per year (NOAA, 2016). Precipitation was generally higher in the summer months (Figure 5), which was driven primarily by the frequency of storm events. In winter months, precipitation most often occurred as snow and ice, averaging about 53 inches of snowfall per year from 1976 to 2015 (NOAA, 2016). July was generally the hottest month of the year and January was typically the coldest (Figure 5).

Figure 5. Metro Area Precipitation, Snowfall, and Temperature (NOAA, 2016)



Ecoregions and Geology

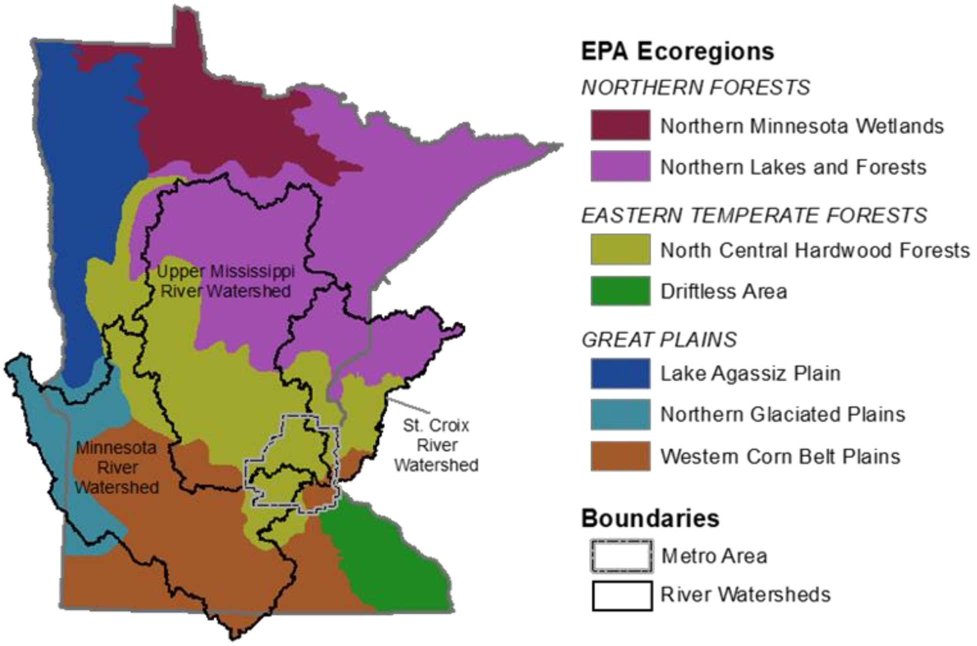
Ecoregions are areas that have similar ecosystems, sharing such characteristics as geology, landforms, soil type, vegetation, climate, land use, wildlife, and hydrology (USEPA, 2016). Waterbodies within an ecoregion therefore often have similar water quality stressors. The Mississippi, Minnesota, and St. Croix river watersheds are part of three major Level II ecoregions of North America: Northern Forests, Eastern Temperate Forests, and the Great Plains. Within these major Level II ecoregions are seven Level III ecoregions, as shown in Figure 6.

The Minnesota River watershed lies mostly in the Western Corn Belt Plains Level III ecoregion (Figure 6), a majority of which has been converted to row crops. The most common stressors of surface waters in this ecoregion are high sediment and nutrient concentrations (MPCA, 2015a). Additionally, the Minnesota River watershed lies in an area with a young geology. As a result, the Minnesota River and its tributaries are still naturally cutting down and transporting large amounts of sediment (MPCA, 2009a). The conversion to farmland has also altered the hydrology of the Minnesota River, increasing flow and accelerating erosion rates (MPCA, 2015b; Schottler et al., 2013).

The northern portions of the Mississippi and St. Croix river watersheds fall in the Northern Lakes and Forests ecoregion (Figure 6). This ecoregion is heavily forested with steep rolling hills interspersed with wetlands and lakes. Agriculture is limited in the area, but there are some beef and dairy cattle farms. Common stressors of surface water in this ecoregion are atmospheric deposition, runoff from logging operations, urban development, mining, and failing septic systems (MPCA ,2015a).

Most of the southern portions of the Mississippi and St. Croix river watersheds, as well as most of the metro area, fall in the North Central Hardwood Forests ecoregion (Figure 6). This ecoregion is best described as a transition area between the forests in the northeast and agricultural land in the southwest. It has many lakes and the terrain varies from hardwood and conifer forests to small agricultural plains. Developed areas are common in this ecoregion, ranging from the highly urban Twin Cities to lakeside development, which can cause water quality problems for the water bodies in the area (MPCA, 2015a).

Figure 6. EPA Level II and III Ecoregions of Minnesota and the River Watersheds (USEPA, 2012a)



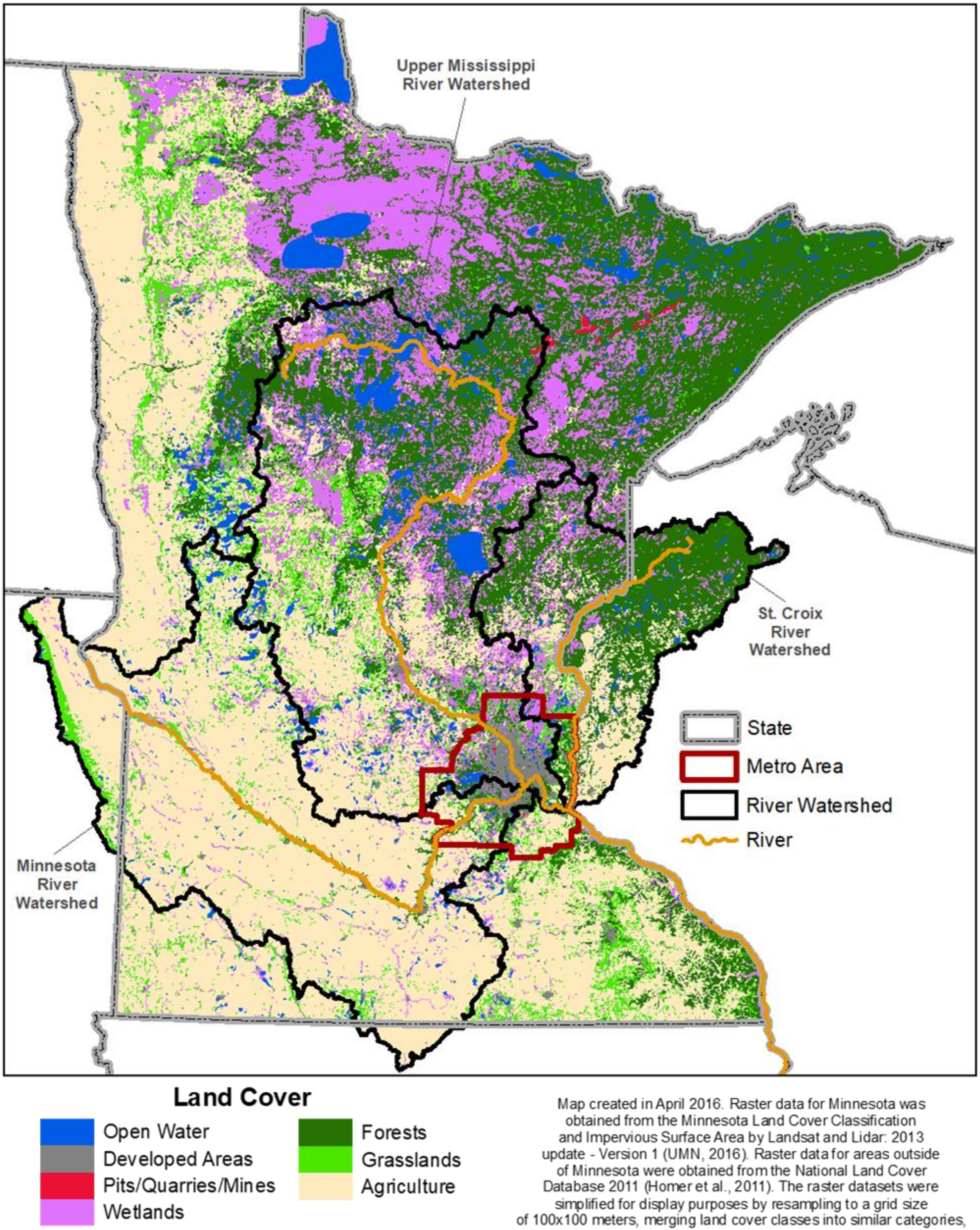
Land Cover

Watershed Land Cover

Human-altered land cover, such as urban and agricultural areas, impact water quality in rivers. Urban areas have a high proportion of impervious surfaces, such as roads, rooftops, parking lots, which prevent precipitation and rainfall from infiltrating into the ground. Instead, the water flows over the land and through storm sewers, potentially picking up pollutants such as fertilizers, road salts, and organic waste along the way. Agricultural areas typically have large expanses of bare soils and are configured to drain away excess water to prevent flooding of crops. The drained water can potentially carry nutrients from the bare soil and fertilizers on the field into the rivers. In both urban and agricultural environments, artificial runoff infrastructure (such as sewers and tile drains), have altered the natural hydrology of the landscape.

Upstream areas impact the water quality of the rivers that enter the metro area. Across Minnesota, the land cover transitions from agriculture in the southwest to forest and wetland in the northeast (Figure 7). Most of the Minnesota River watershed is agricultural, whereas the St. Croix River watershed consists mostly of natural areas such as forest and wetlands, as shown in Figure 8 and Table 1. The Upper Mississippi River watershed has a more balanced mix of agricultural and natural areas.

Figure 7. Simplified Land Cover of Upper Mississippi, Minnesota, and St. Croix River Watersheds



Map created in April 2016. Raster data for Minnesota was obtained from the Minnesota Land Cover Classification and Impervious Surface Area by Landsat and Lidar: 2013 update - Version 1 (UMN, 2016). Raster data for areas outside of Minnesota were obtained from the National Land Cover Database 2011 (Homer et al., 2011). The raster datasets were simplified for display purposes by resampling to a grid size of 100x100 meters, merging land cover classes into similar categories, and generalizing the map using tools in ArcGIS (Esri, 2012).

Figure 8. Land Cover of the Upper Mississippi, Minnesota, and St. Croix River Watersheds (Homer et al., 2011; UMN, 2016)

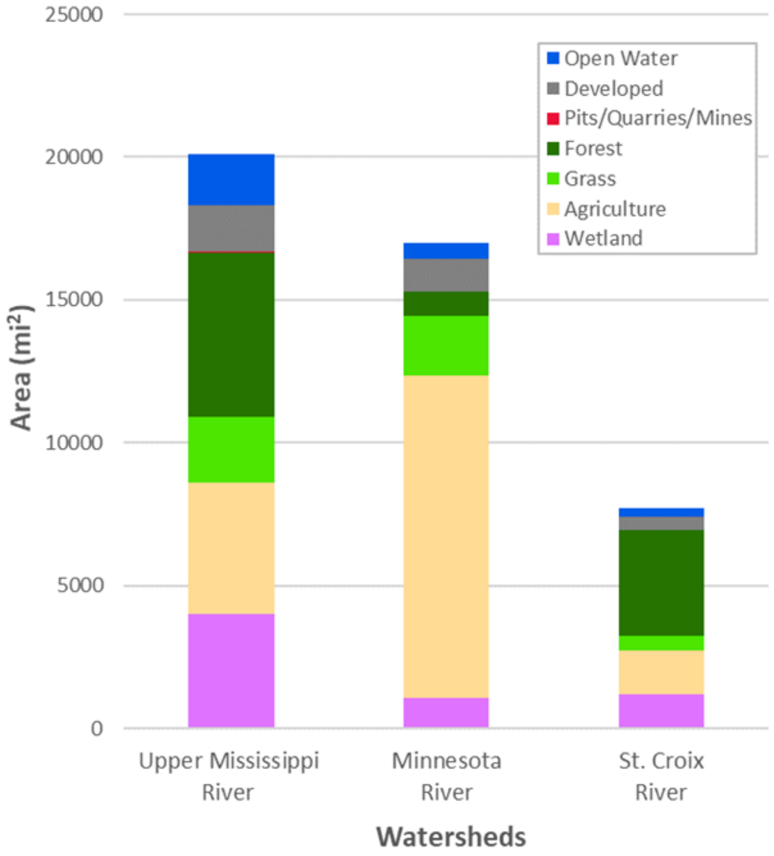


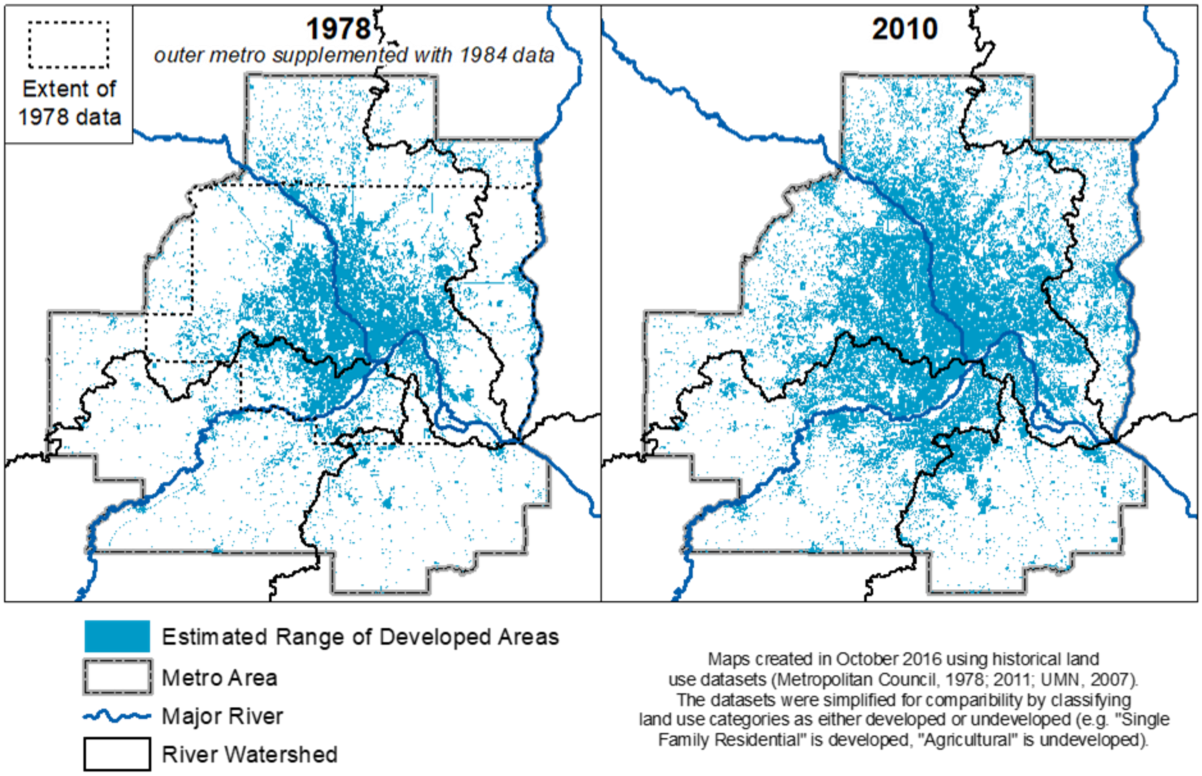
Table 1. Land Cover of the Upper Mississippi, Minnesota, and St. Croix River Watersheds (Homer et al., 2011; UMN, 2016)

Land Cover	Upper Mississippi River Watershed		Minnesota River Watershed		St. Croix River Watershed	
	Area (mi²)	*% of watershed*	*Area (mi²)*	*% of watershed*	*Area (mi²)*	*% of watershed*
Open Water	1,765	9	560	3	311	4
Developed	1,654	8	1,168	7	457	6
Pits/Quarries/Mines	23	< 1	5	< 1	4	< 1
Forest	5,759	29	843	5	3,717	48
Grass	2,274	11	2,096	12	512	7
Agriculture	4,608	23	11,264	66	1,516	20
Wetland	4,018	20	1,072	6	1,200	16

Development of the Metro Area

The amount of developed land (that is, areas with impervious surfaces, mainly associated with human activity such as residential, commercial, and industrial land use) in the metro area has increased steadily over the past several decades (Figure 9). Metropolitan Council's historical land use datasets roughly estimate that the developed portion of the metro area increased from 16% to 31% from the late 1970s to 2010 (Metropolitan Council, 1978; 2011; UMN, 2007). A detailed study determined that developed land in the metro area increased from 23.7% to 32.8% from 1986 to 2002 while rural cover (agricultural, forest, and wetland) decreased from 69.6% to 60.5% (Yuan et al., 2005). The Metropolitan Council forecasts that developed areas will continue to expand through the coming decades (Metropolitan Council, 2016).

Figure 9. Development Progression in the Metro Area



Maps created in October 2016 using historical land use datasets (Metropolitan Council, 1978; 2011; UMN, 2007). The datasets were simplified for comparibility by classifying land use categories as either developed or undeveloped (e.g. "Single Family Residential" is developed, "Agricultural" is undeveloped).

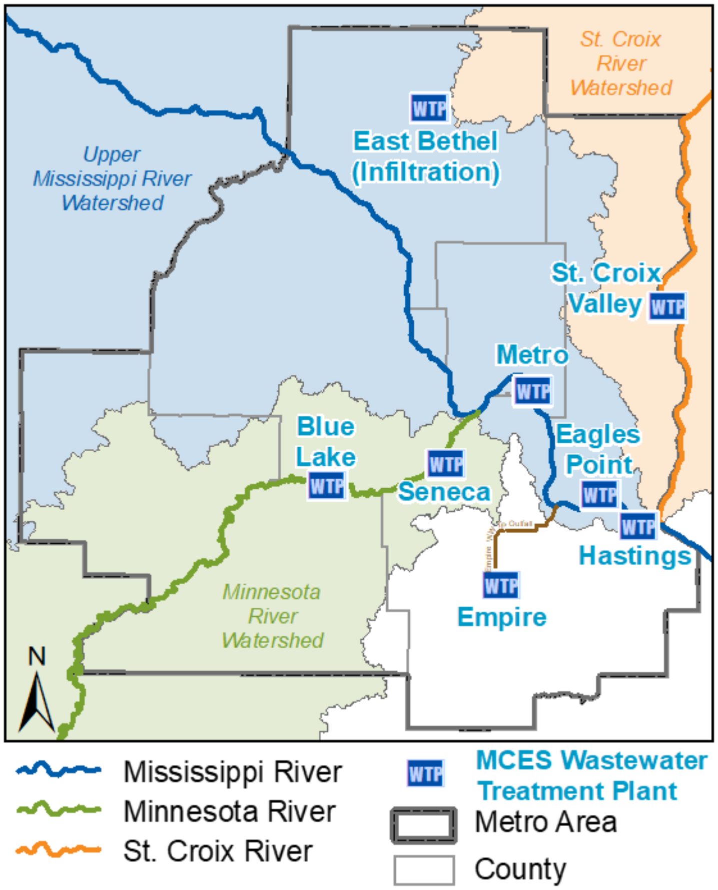
Current Environmental Conditions

Sources of Pollution

Pollutants that impact water quality enter rivers from both point and nonpoint sources. Point sources are identifiable, discrete locations, like pipe outfalls, whereas nonpoint sources are diffuse and pollutants come from a wide area. Common point sources include WWTPs, feedlots, and municipal stormwater. Main nonpoint sources include tributaries, direct runoff into rivers from adjacent land, and atmospheric deposition of minute particles.

MCES operates eight WWTPs in the metro area, including some of the largest in the state (Table 2). Seven of the WWTPs discharge treated wastewater into rivers (Figure 10). The Empire WWTP discharge was rerouted in 2008 from the Vermillion River to the Mississippi River, to protect the environmental conditions in the Vermillion River. East Bethel is a water reclamation facility which infiltrates highly treated wastewater ("reclaimed water") into the ground.

Figure 10. MCES Wastewater Treatment Plant Locations



As of 2016, there were 333 permitted municipal wastewater discharge locations in the Upper Mississippi River watershed and 240 and 76, respectively, in the Minnesota portion of the Minnesota and St. Croix river watersheds. Most of these discharge locations are upstream of the metro area (Figure 11).

There were approximately 34,473 registered feedlots in Minnesota as of 2016, widely ranging in size from less than one animal unit up to nearly 19,500 (Figure 12). A total of 1,226 feedlots were in the metro area, mostly in the south and west. Feedlots in Minnesota are registered with the MPCA if they have more than 10 animal units in shoreland or more than 50 animal units outside shoreland. Additionally, MPCA’s dataset includes feedlots of owners that choose to register voluntarily or if they are in a county that has more stringent registration requirements than the MPCA. There were approximately 8,990 feedlots in the Upper Mississippi river watershed and 10,050 and 503 feedlots, respectively, in the Minnesota and St. Croix river watersheds.

Stormwater runoff is a source of pollution for nearby surface waters in the metro area, transporting pollutants such as fertilizers, salt, sediment, and other debris from impervious surfaces. In urban areas, this pollutant transport occurs via a system of conveyances that include roads, curbs, gutters, ditches, storm drains, and storm sewers. Publicly owned and operated conveyance systems used only for stormwater in urban areas are called Municipal Separate Storm Sewer Systems (MS4s). In Minnesota, the MPCA issues general permits for MS4s under the federal Clean Water Act. These permits aim to reduce the stormwater pollutants that are discharged from MS4s into regional surface waters, including lakes, streams, and rivers. Under the MS4 permit, the system owners/operators are required to develop a Stormwater Pollution Prevention Program, which details the stormwater BMPs that will be used to meet the pollution restrictions of the MS4 permit. As of 2017, there were 255 MS4s in Minnesota, with 160 of those located in the metro area (MPCA, 2017a).

Metro area tributaries also carry pollutants into the major regional rivers. Tributaries are considered nonpoint sources, because their water quality is affected by diffuse factors within their watersheds, including land cover, land use, geology, and pollutants generated by human activities, such as fertilization/pesticide use and road-salt application. Most of the main tributaries to the rivers in the metro area are monitored by MCES or other entities. In 2014, MCES released a comprehensive report examining the water quality of 21 streams in the metro area, which are all tributaries of the Mississippi, Minnesota, and St. Croix rivers (MCES, 2014).

Another source of nonpoint pollution is atmospheric deposition. Pollutants in the atmosphere such as metals (including mercury), nitrogen, and phosphorus from both natural and human sources are deposited into water bodies and their watersheds.

The water quality of each river can be affected by the combinations of point and nonpoint sources in the watershed. For example, the MPCA estimated that the majority of the nitrogen load to surface waters in the Minnesota River watershed originates from tile drainage and cropland groundwater (MPCA, 2013). In comparison, the nitrogen loading to surface waters in the Upper Mississippi and St. Croix river watersheds also has substantial contributions from forests, atmospheric deposition, and WWTPs (MPCA, 2013).

Figure 11. Permitted Municipal Wastewater Treatment Plants in Minnesota (MPCA, 2015c)

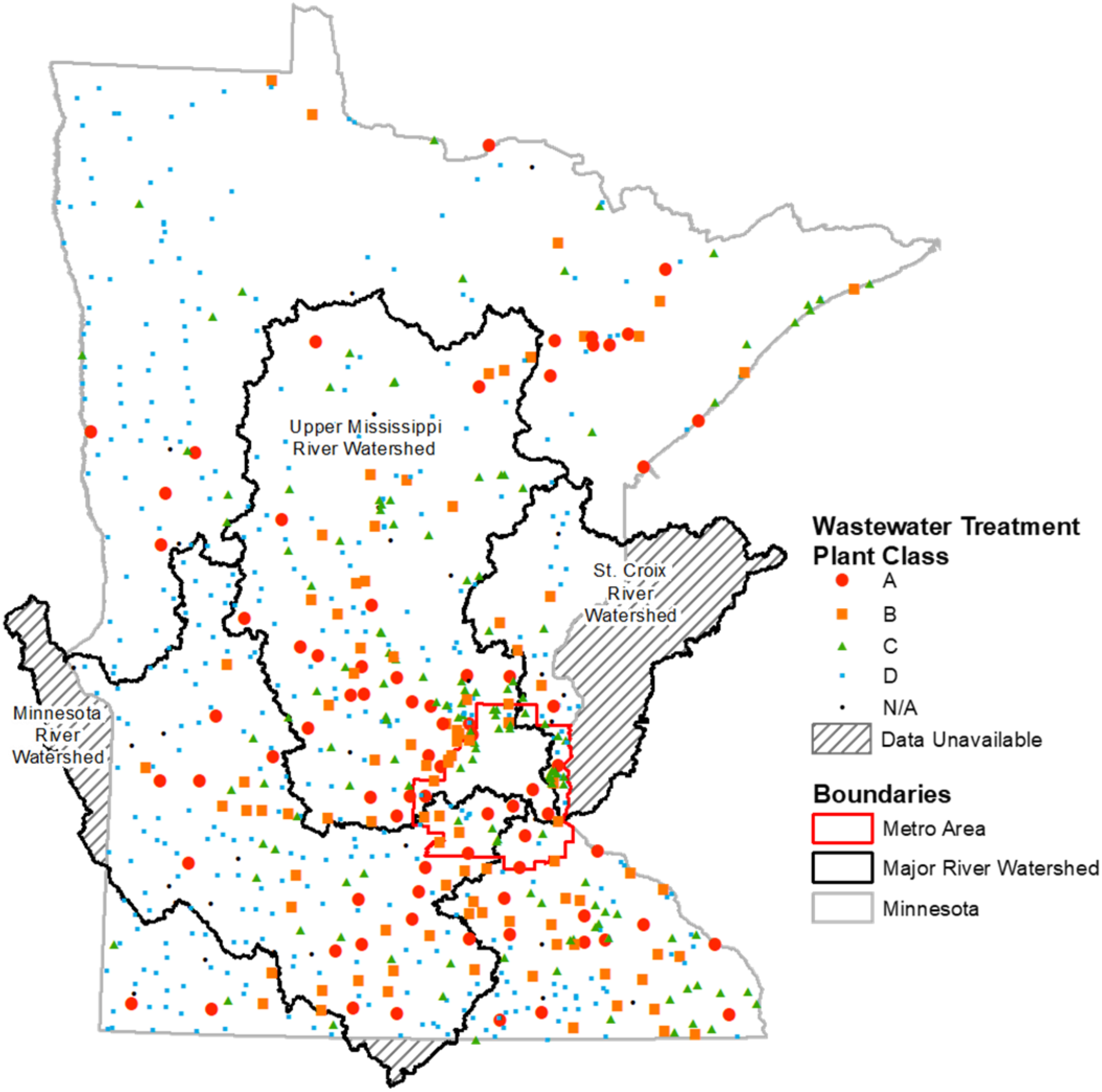


Figure 12. Distribution of Registered Feedlots in Minnesota (MPCA, 2016b)

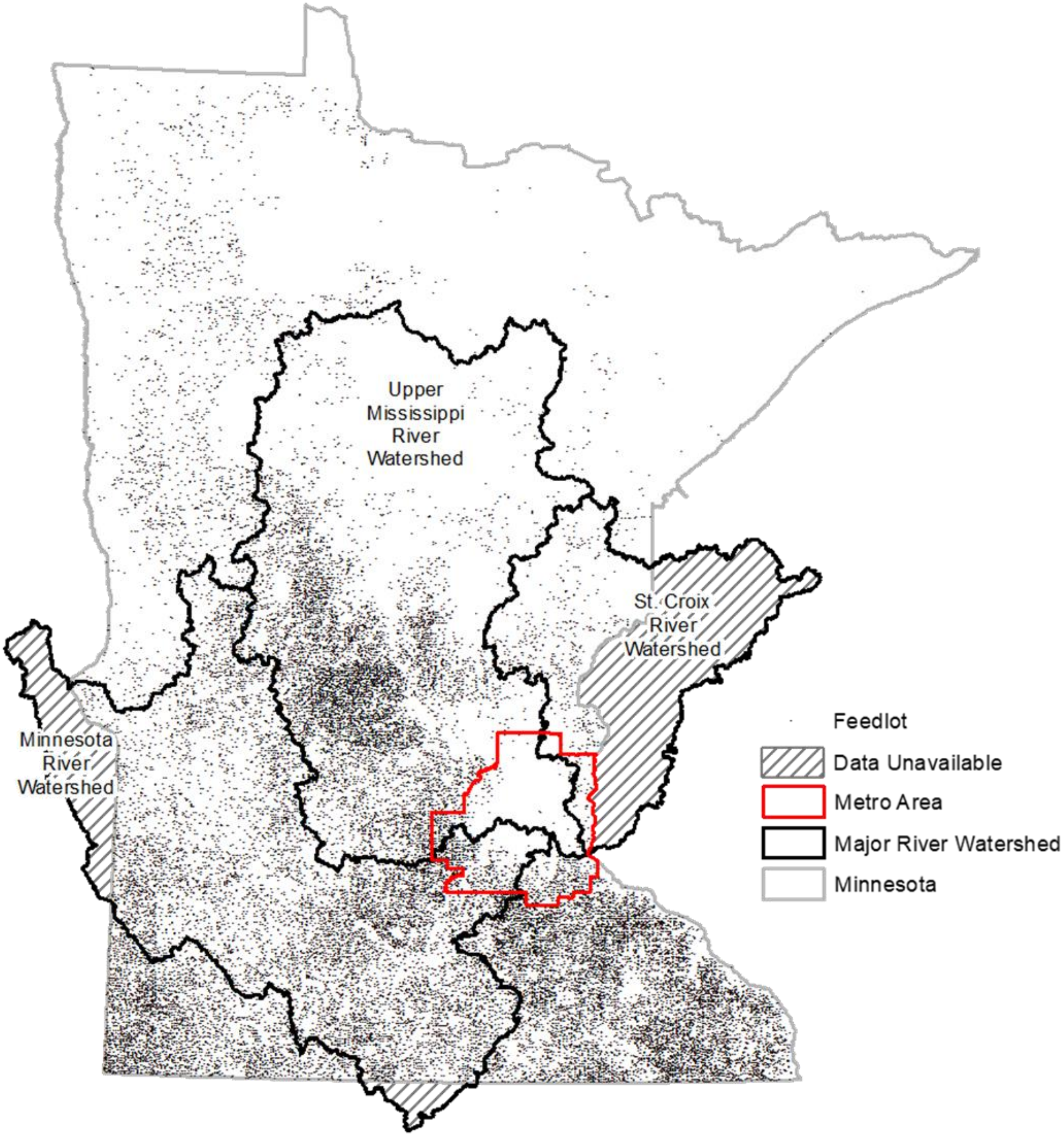


Table 2. MCES Wastewater Treatment Plants in the Metro Area

Name	City	County	Start of operation	Start of phosphorus removal installations	Capacity (MGD)	2015 median daily flow (MGD)	Receiving waters	Closest downstream MCES river sampling location
Blue Lake	Shakopee	Scott	1971	2009	32	24	Minnesota River	Minnesota River at Fort Snelling
Eagles Point [a]	Cottage Grove	Washington	2002	2005	10	4.4	Mississippi River	Mississippi River above Lock & Dam 2
East Bethel [b]	East Bethel	Anoka	2014	2014	0.44	0.03	Groundwater Infiltration	NA
Empire [c]	Empire Township	Dakota	1979	2005	24	10	Mississippi River	Mississippi River above Lock & Dam 2
Hastings	Hastings	Dakota	1955	No P removal	2.34	1.42	Mississippi River	Mississippi River above Lock & Dam 3
Metro	Saint Paul	Ramsey	1938	1999	251	167	Mississippi River	Mississippi River at Grey Cloud Island
Seneca	Eagan	Dakota	1972	2001	34	21	Minnesota River	Minnesota River at Fort Snelling
St. Croix Valley	Oak Park Heights	Washington	1959	1973	4.5	2.9	St. Croix River	St. Croix River at Prescott

[a] Eagles Point replaced the Cottage Grove WWTP, which was in operation since 1962.
[b] East Bethel is a water reclamation facility that infiltrates highly treated wastewater (“reclaimed water”) into the ground instead of discharging into surface waters.
[c] Until 2008, the Empire WWTP discharged to the Vermillion River.

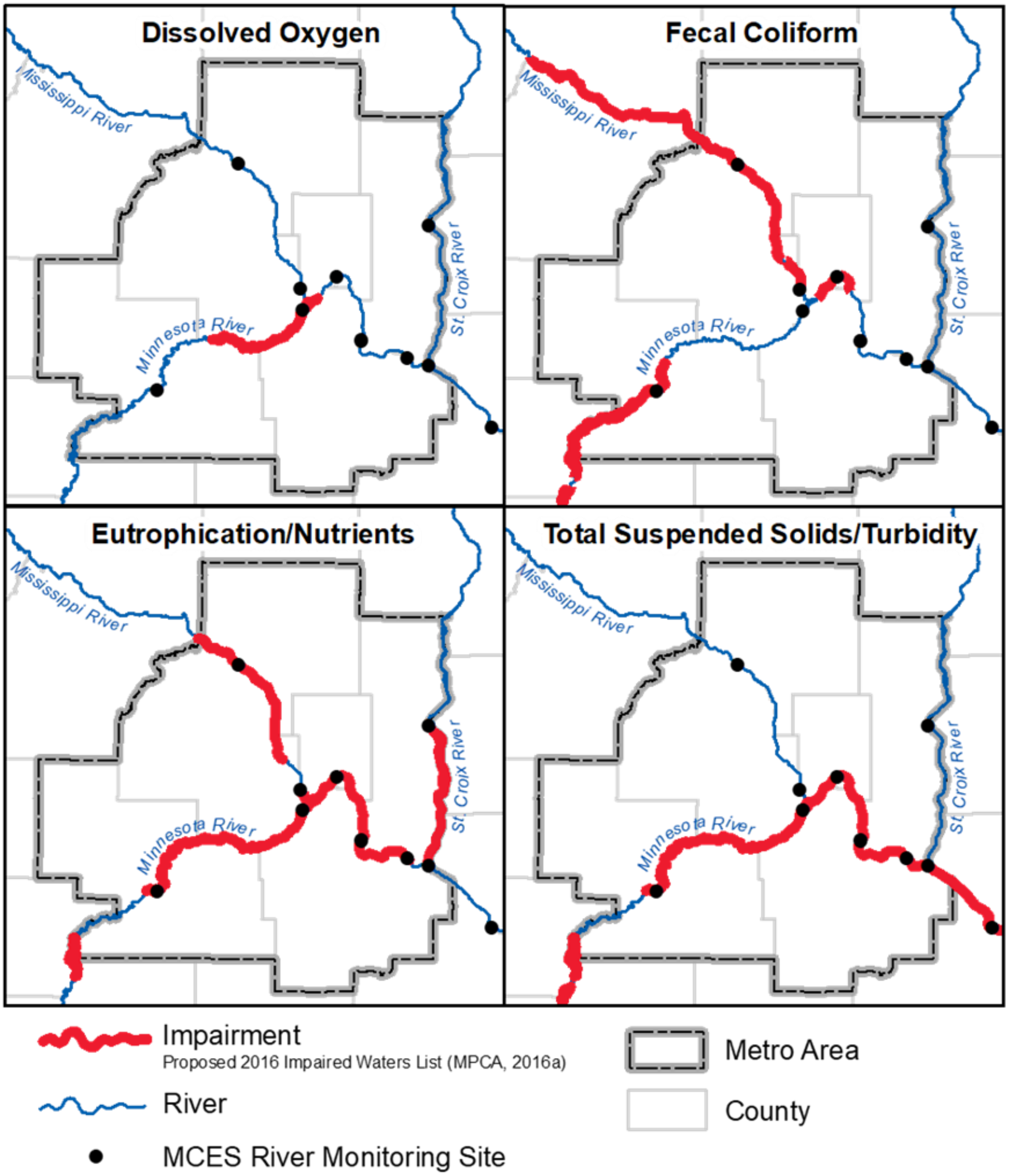
Metro Area River Impairments

The MPCA has established water quality standards as part of the 1972 Clean Water Act. These standards set limits for the pollutant levels in Minnesota's surface waters. A standard typically consists of a numerical value and conditions specifying when, how often, and by how much that value is allowed or not allowed to be exceeded. If the MPCA has determined that a standard has been violated, they may classify the water body as impaired, which begins a process of planning how to meet the water quality standards moving forward.

Every two years, the MPCA creates an Impaired Waters List – also known as a 303(d) list – detailing the impairments of Minnesota's surface waters. Data from the MCES monitoring programs are used by the MPCA to help detect impairments. According to the draft 2016 Impaired Waters List, every stretch of river in the metro area has at least one impairment (MPCA, 2016a). Impairments involving the parameters in this study are shown in Figure 13. Additional impairments in the rivers of the metro area include mercury, polychlorinated biphenyls (PCBs), and perfluorooctanesulfonic acid (PFOS) in fish tissue and/or the water column.

The Mississippi and Minnesota rivers have impairments for FC and sediment (Figure 13). In this context, sediment is defined as an impairment of either TSS or turbidity. The MPCA set standards for TSS in 2014, replacing the previous turbidity standard. Minnesota's river eutrophication standard, set in 2015, defines a eutrophication impairment (sometimes called a nutrient impairment) as the exceedance of a TP criteria (the causation criteria) as well as the criteria of either Chl-*a*, BOD_5, diel DO flux, or pH (the response criteria) (MPCA, 2015d). The lake eutrophication standard, which applies to Lake St. Croix, only considers the response criteria of Chl-*a* and Secchi depth (Heiskary and Wilson, 2008). Stretches of all three rivers have eutrophication impairments in the metro area. The only river impairment for DO in the metro area is in a portion of the Minnesota River.

Figure 13. Dissolved Oxygen, Fecal Coliform, Eutrophication/Nutrient, and Total Suspended Solids / Turbidity Impairments of the Rivers in the Metro Area (MPCA, 2016a)



Pollution Control Efforts

Efforts in past decades and recent years have helped to protect and improve the water quality of surface waters in the metro area, including water-related infrastructure improvements, a wide range of regional, state, and federal regulations, and local pollution control efforts. Combined, they have the potential to greatly improve the water quality of regional rivers over time.

In addition, upgrades of regional WWTPs have progressively reduced pollutant concentrations discharged to receiving waters and handled larger volumes of wastewater as the population of the metro area has grown. Construction of the original Minneapolis-Saint Paul Sewage Treatment Plant – later named the Metro WWTP – in 1938 provided primary treatment, a major advance at the time. Secondary treatment technology was implemented at the Metro WWTP in 1966 and advanced secondary treatment technology in 1984. For more detail on the improvements to WWTP in the region, MWCC (1988) provides a 50-year history (1938-1988) of regional wastewater treatment improvements.

More recently:

- The combination of technology improvements has significantly decreased BOD and TSS concentrations in WWTP treatment plant discharges. The mean annual Metro WWTP concentration of TSS has decreased 98% since 1966 (MCES unpublished data accessed Dec. 2017).
- The implementation of a biological nitrification process has resulted in a 679% decrease in NH_3 concentrations in Metro WWTP discharges (Lafrancois et al., 2013).
- Phosphorus removal technology has been installed at seven of MCES's WWTPs (Table 2). At the Metro WWTP, there has been a 92% reduction in discharge phosphorus loads since biological phosphorus (Bio-P) removal technology was implemented in 1999 (Metropolitan Council, 2015).

The infrastructure of the conveyance network carrying wastewater to the WWTPs has experienced upgrades:

- Between 1985 and 1995, most of the sewers in Minneapolis and Saint Paul were converted from a combined system into two separate wastewater and stormwater systems. The previous combined-sewer system allowed raw sewage to overflow directly into the rivers when the volume exceeded their capacity during large storms.
- MCES has established a multiyear capital improvement program to preserve and rehabilitate existing wastewater infrastructure (including treatment plants and interceptors), meet more stringent water and air quality regulations, and expand the system capacity to meet regional growth needs.

Regulations at the regional, state, and federal levels have also contributed to pollution control. These regulations address issues such as restricting the use of phosphorus fertilizers on lawns, requiring industrial facilities to pretreat their wastewater before releasing it to WWTPs, and setting water quality standards in response to the 1972 Clean Water Act.

In addition to regulations, a wide range of programs serve to protect and restore Minnesota's water quality. For example, the MPCA has identified 39 programs from eight different regional, state, and federal agencies that in some way address nutrient reduction in Minnesota's waters (MPCA, 2014). A table describing each of these programs can be found in the Minnesota Nutrient Reduction Strategy published by the MPCA in 2014.

Organizations at the local level are doing their part to reduce pollution as well. Groups such as watershed management organizations (WMOs), watershed districts (WDs), soil and water conservation districts (SWCDs), cities, townships, and, private development communities have an interest in keeping Minnesota’s waters clean. These organizations often focus on overseeing conservation projects locally, such as working with residents to install and maintain BMPs to reduce pollution entering surface waters. BMPs include installations such as rain gardens, vegetated buffer strips, and erosion control. While these projects are typically smaller scale, having a variety of them throughout the watershed may have a cumulative effect to influence surface water quality. Additionally, these local groups can focus on implementing larger projects throughout the entire watershed.

STUDY METHODS

Monitoring Sites and Parameters

Monitoring Sites

This study used water quality data from 10 primary sites that are part of the MCES river monitoring program (Figure 14). The sites were established in 1976 at key points along the Mississippi, Minnesota, and St. Croix rivers, including upstream and downstream of WWTP discharge locations and at the entrance and exit points of the rivers from the metro area. The significance of these site is evident in the locations described in Table 3.

The Mississippi River enters the metro area from the northwest at the border of Anoka and Hennepin counties. From the first monitoring site at Anoka, the river flows through mostly developed areas, including the highly urban center of Minneapolis, and then reaches the monitoring site at Lock and Dam 1.

Downstream from Saint Paul, the Metro WWTP discharges to the Mississippi River. The Metro WWTP is one of the largest in the nation, treating an average of 170 million gallons of wastewater per day. Downstream from the Metro WWTP discharge channel is the monitoring site at Grey Cloud Island.

Treated wastewater from the smaller Empire and Eagles Point WWTPs enters the Mississippi River before it reaches the monitoring site at Lock and Dam 2. Just downstream from Lock and Dam 2, the Hastings WWTP discharges to the river, and the St. Croix River enters the Mississippi at Prescott, Wisconsin. The monitoring site at Lock and Dam 3 captures the quality of the river leaving the metro area.

The Minnesota River enters the metro area on the extreme southwest and then flows to the monitoring site at Jordan. The site at Fort Snelling monitors the water quality of the river downstream of the discharges from the Blue Lake and Seneca WWTPs and upstream of the river’s confluence with the Mississippi River.

The St. Croix River site at Stillwater monitors the water quality of the river entering the metro area and upstream of the St. Croix Valley WWTP discharge. The site at Prescott, Wisconsin, monitors the river at the outlet of Lake St. Croix, near the confluence with the Mississippi River.

Water Quality Parameters

The water quality parameters included in this study are listed in Table 4. With a few exceptions, the parameters have been routinely monitored at all 10 river sites since 1976. Exceptions include Cl and *E. coli*, which were not monitored until 1985 and 2005, respectively. Additionally, measurement of TN, NH_3, NO_3, TP, and Chl-*a* in the Minnesota River at Jordan did not begin until 1979.

Figure 14. MCES River Monitoring Sites and WWTP Locations

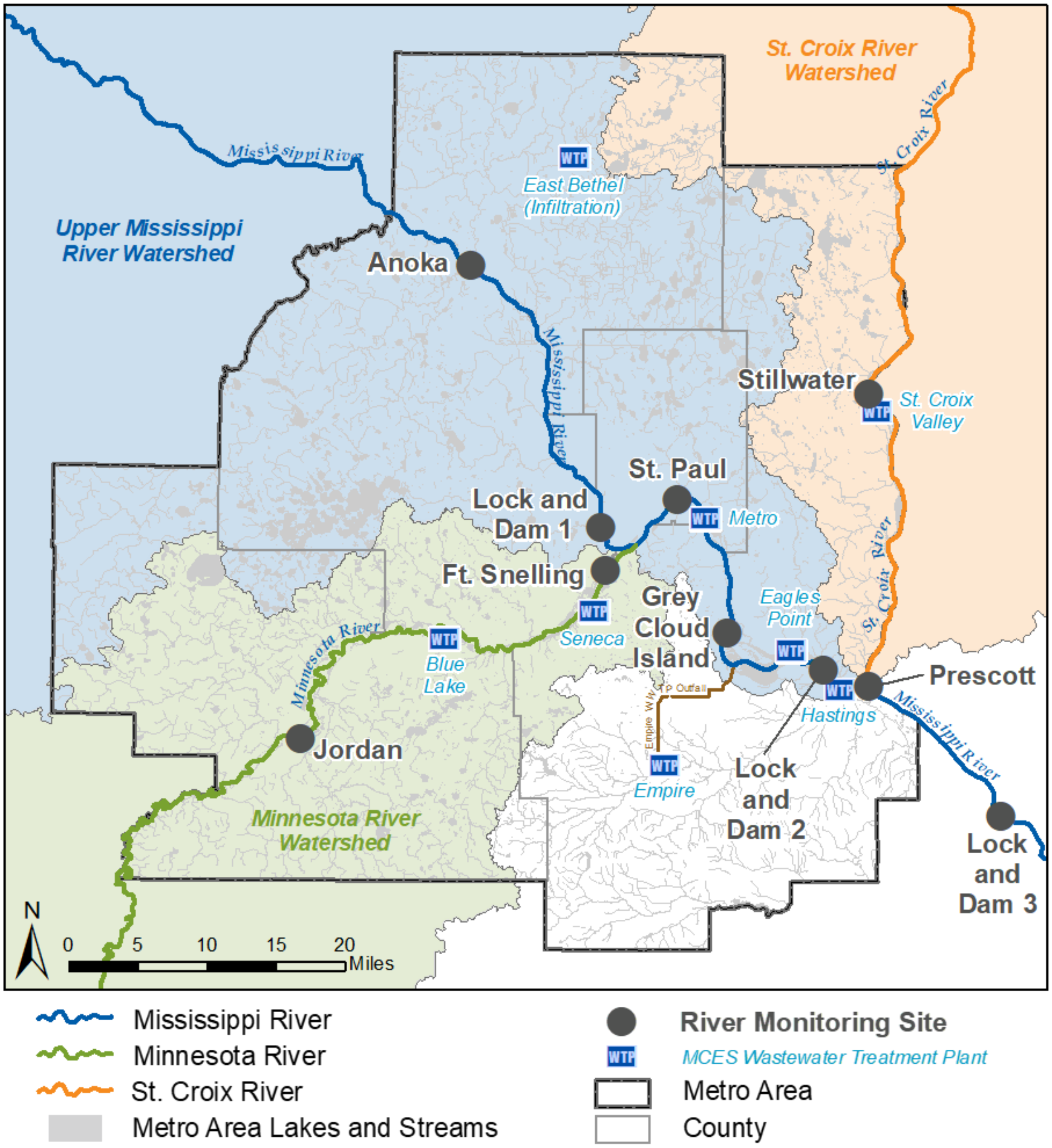


Table 3. River Monitoring Site Descriptions

Site	Significance
Mississippi River	
Anoka *River Mile 871.6*	• Entrance of the Mississippi River into the metro area • Upstream of the highly urbanized Minneapolis-Saint Paul core
Lock and Dam 1 *River Mile 847.7*	• Downstream of the highly urbanized Minneapolis core • Upstream of the Minnesota River confluence • Immediately upstream of Lock and Dam 1
Saint Paul *River Mile 839.1*	• Downstream of the Minnesota River confluence • Upstream of the Metro WWTP discharge
Grey Cloud Island *River Mile 826.7*	• Downstream of the large Metro WWTP discharge channel • Historically has been a stressed section of the river
Lock and Dam 2 *River Mile 815.6*	• Upstream of the St. Croix River confluence • Downstream of the Eagles Point and Empire WWTPs' discharges • Downstream of the highly urbanized Minneapolis-Saint Paul core • Immediately upstream of Lock and Dam 2
Lock and Dam 3 *River Mile 796.9*	• Downstream of the St. Croix River confluence • Downstream of the Hastings WWTP discharge • Exit of the Mississippi River from the metro area • Immediately upstream of Lock and Dam 3
Minnesota River	
Jordan *River Mile 39.4*	• Entrance of the Minnesota River into the metro area • Upstream of the Blue Lake and Seneca WWTPs' discharges
Fort Snelling *River Mile 3.5*	• Downstream of the Blue Lake and Seneca WWTPs' discharges • Near the river confluence with the Mississippi River
St. Croix River	
Stillwater *River Mile 23.3*	• Entrance of the St. Croix River into the metro area • Upstream of the St. Croix Valley WWTP discharge
Prescott *River Mile 0.3*	• Downstream of the St. Croix Valley WWTP discharge • At the outlet of Lake St. Croix • Near the river confluence with the Mississippi River

Table 4. Water Quality Parameters

Used in statistical trend (QWTREND) as well as annual and monthly pattern analysis	Used only in annual and monthly pattern analysis
5-Day Biochemical Oxygen Demand (BOD_5)	Conductivity
Ammonia-Nitrogen (NH_3)	Dissolved Oxygen (DO)
Chloride (Cl)	*Escherichia coli* Bacteria (*E. coli*)
Corrected Chlorophyll-*a* (Chl-*a*)	Flow (Q)
Fecal Coliform Bacteria (FC)	pH
Nitrate-Nitrogen (NO_3)	Water Temperature
Total Nitrogen (TN)	
Total Phosphorus (TP)	
Total Suspended Solids (TSS)	

Uncorrected and Corrected Chlorophyll. MCES measured uncorrected chlorophyll-*a* from 1976 to 2000 and pheophytin corrected chlorophyll-*a* as well from 2001 onward. Corrected chlorophyll-*a* is more commonly used by water professionals to evaluate the condition of a site because it is more representative of living algal biomass in the water.

MCES developed site-specific regressions between measured corrected and uncorrected chlorophyll-*a* using data from 2001 onward. These regressions were used to estimate corrected chlorophyll-*a* concentrations from uncorrected chlorophyll-*a* concentrations from 1976 to 2015. To assess how well the regressions estimated corrected concentrations from the uncorrected, the estimated corrected chlorophyll-*a* concentrations were compared to the measured corrected chlorophyll-*a* concentrations from 2001 to 2015. On average, the estimated concentrations were only about 4% lower than the measured concentrations, and a regression between the estimated and measured concentrations had an R-squared of 0.963. This indicated a strong relationship to accurately estimate corrected chlorophyll-*a* concentrations. For this report, the estimated corrected chlorophyll-*a* concentrations from 1976 to 2000 were merged with the measured corrected chlorophyll-*a* concentrations from 2001 to 2015 to produce a cohesive record from 1976 to 2015. Henceforth, “Chl-*a*” refers to “corrected Chl-*a*” and is the combined dataset of estimated corrected Chl-*a* data from 1976 to 2000 with the measured corrected Chl-*a* data from 2001 to 2015.

Chloride. The Cl data were collected as both filtered and unfiltered. Theoretically, the results of a filtered and unfiltered Cl sample should be the same since Cl is a dissolved ion. The filtered and unfiltered Cl data were merged. If filtered and unfiltered Cl samples were taken on the same day, the unfiltered result was used.

Ammonia-Nitrogen. In this report, NH_3 refers to the combined sum of the nitrogen in un-ionized ammonia and ammonium. Additionally, all conductivity results have been corrected to 25 °C (that is, specific conductance).

Sample Collection and Processing

Sample Collection

Begun in 1976, the MCES river monitoring program spans the 40-year period represented in this report. Water samples were collected weekly at each monitoring site during warmer months (March–October) and every other week in winter (November–February), ice conditions permitting. Samples were taken at one meter below the water surface at the designated monitoring sites (Figure 14 and Table 3).

The collected water was transferred into a sample container, stored on ice in a cooler, and transported to the MCES laboratory within six hours for analysis. Additionally, a multi-parameter sonde measured DO, pH, temperature, and conductivity at the sampling station. In the rare cases when a site was inaccessible, samples were collected at a nearby location. Details of these situations are listed in Table 5.

Table 5: Temporary Monitoring Site Substitutions Due to Inaccessibility

Site	Dates Inaccessible	Reason	Substitute Site
Mississippi River at Saint Paul, river mile 839.1	Periodic winter samples	Ice cover	River mile 836.8
Minnesota River at Jordan, river mile 39.4	August 2001–August 2002	Bridge construction	River mile 25.1
St. Croix River at Stillwater, river mile 23.3	August–December 2005 August–December 2012	Bridge construction	River mile 23.4

Laboratory Analysis

Water samples were processed and analyzed by the MCES Analytical Services Section (laboratory), located at the Metro WWTP in Saint Paul. The MCES lab is certified by the Minnesota Department of Health (certification number 027-123-172). The methods used for the parameters as of 2015 are listed in Table 6. Each method has a reporting limit (RL), which is the lowest concentration the lab generally reports for a given method. RLs are listed alongside their analytical methods in Table 6. Refer to “Data Analysis Methods” for information about how data below the RLs were treated for this study.

The methods and RLs may have changed over time as analytical techniques were updated and instrument accuracy improved. These changes can create uncertainty in trend results, with the potential to mask trends or create artificial trends in some cases.

Daily Average Flows

Daily average river flows were obtained from USGS gauging stations near MCES monitoring sites, except for Mississippi River flows at Lock and Dam 1, which were obtained from the USACE (Table 7). The MCES Mississippi River monitoring sites at Anoka and at Grey Cloud Island did not have representative flow measurement gauges nearby. For these sites, flows were calculated using alternative flow monitoring sites.

The MCES monitoring site at Anoka is located upstream of where the Rum River and Elm Creek join the Mississippi River, but the USGS gage is located downstream of these two tributaries in Brooklyn Park. Therefore, flow at Anoka was calculated as the flow of the Mississippi River at Brooklyn Park minus the measured flows of those two tributaries. The MCES monitoring site at Grey Cloud Island is located downstream of the Metro WWTP, so the flow at this location was calculated by adding the

Metro WWTP daily average influent flow (assumed to be equal to the effluent discharge flow) to the flow of the Mississippi River measured upstream of the Metro WWTP at Saint Paul.

Table 6. Laboratory Analytical Methods as of 2015

Laboratory Parameter	Reference Method [a]	RL	RL Unit
BOD_5	SM 5210 B-2001, Hach 10360 Rev. 1.1	0.2	mg/L
Chl-*a*	ASTM D3731-87	1	ug/L
Cl	SM 4500-Cl^- E-1997	2	mg/L
DO [b]	SM 4500-O C-2001	0.05	mg/L
E. coli	SM 9223B-1997 (Colilert-18 Quanti Tray)	1	MPN/100 mL
FC	USEPA 600/8-78-017	1	cfu/100 mL
NH_3	USEPA 350.1 Rev 2.0	0.06 [c]	mg/L
NO_3 and nitrate-nitrite nitrogen (NO_3-NO_2)	SM 4500-NO_3^- H-2000 (ATP)	0.05	mg/L
Total Kjeldahl Nitrogen (TKN)	USEPA 351.2 Rev 2.0	0.1	mg/L
TN	TKN + NO_3-NO_2	NA	NA
TP	USEPA 365.4, 1974	0.05 [d]	mg/L
TSS	SM 2540D-1997 (ATP)	3	mg/L

[a] SM = Standard Methods for the Examination of Water and Wastewater
ASTM = ASTM International; American Society for Testing and Materials
USEPA = U.S. Environmental Protection Agency
USGS = United States Geological Survey
ATP = Alternative Test Procedures granted by the USEPA

[b] Performed only in winter months when freezing temperatures diminish the accuracy of the field DO probe

[c] Since 2000, the laboratory has reported NH_3 down to 0.02 mg/L, although the official reporting limit has remained at 0.06 mg/L

[d] Since 2000, the laboratory has reported TP down to 0.01 mg/L, although the official reporting limit has remained at 0.05 mg/L

Table 7. Flow Measurement Sites

Site	Flow Measurement Source [a]
Mississippi River	
Anoka	***1976 - 9/30/1978:*** Calculated as (USGS site 05288500) - (MCES estimation of Elm Creek flow) - (MCES site at Rum River, Mile 0.6) ***10/1/1978 - 2011:*** Calculated as (USGS site 05288500) - (USGS site 05286000) - (MCES site at Rum River, Mile 0.6) ***2011 - 2015:*** Calculated as (USGS site 05288500) - (USGS site 05287890) - (MCES site at Rum River, Mile 0.6)
Lock and Dam 1	***1976 - 1984:*** Calculated by MCES staff using regression equations [b] ***1985 - 2015:*** USACE site at Lock and Dam 1
Saint Paul	***1976 - 2015:*** USGS site 05331000
Grey Cloud Island	Calculated as (USGS site 05331000) + (Metro WWTP Influent)
Lock and Dam 2	***1976 - 9/30/1995:*** Calculated by MCES staff using regression equations [b] ***10/1/1995 - 2015:*** USGS site 05331580
Lock and Dam 3	***1976 - 2015:*** USGS site 05344500
Minnesota River	
Jordan	***1976 - 2015:*** USGS site 05330000
Fort Snelling	***1976 - 2/17/2004:*** Calculated by MCES staff using regression equations [b] ***2/18/2004 - 2015:*** USGS site 05330920
St. Croix River	
Stillwater	***1976 - 9/8/2011:*** Calculated using regression equation developed in Ziegeweid and Magdalene (2015) using data from USGS site 05340500 ***9/9/2011 - 2015:*** USGS site 05341550
Prescott	***1976 - 8/19/2007:*** Calculated using regression equation developed in Ziegeweid and Magdalene (2015) using data from USGS site 05340500 ***8/20/2007 - 2015:*** USGS site 05344490

[a] USGS = United States Geological Survey
USACE = United States Army Corps of Engineers
[b] Refer to MCES (2012) for more information on MCES regression calculations

Data Analysis Methods

Preparation of Water Quality Data for Analysis

The data used in this study are publicly available and can be downloaded from the Environmental Information Management System at ***https://eims.metc.state.mn.us/***. Data points were processed using the following conditions:

- If a parameter result was reported at or less than the RL of the analytical method, the value of the RL was used. If more than 10% of the data was below the RL for a given parameter at a given site, numerical trend results were not reported to avoid any bias the RL may have caused in the trend calculation. This treatment of RLs was recommended by the developer of the QWTREND model (Vecchia, 2017 personal communication). Only a small percentage of samples fell at or below the reporting limit for most parameters at most sites.
- If multiple samples of the same parameter were taken on the same day (i.e. field replicates), the values were averaged.

Annual and Monthly Median Analysis

Concentrations of water quality parameters from grab samples represent the condition of the river at the exact point in time the sample was collected. Plotting these measured concentrations over time can provide a general indication about the overall conditions of the rivers. To summarize the patterns of measured concentrations over time, annual and monthly medians were calculated and plotted for each of the river sites. Medians were used instead of means because water quality data generally have a handful of samples with high concentrations. Means are more skewed by these few high concentrations, whereas medians are more robust and are a better representation of the most “typical” concentrations in the data.

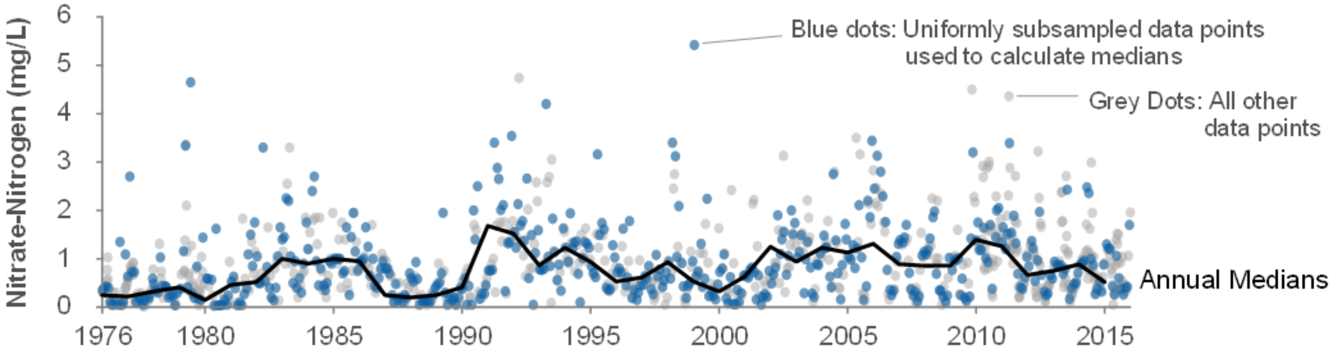
Calculating Medians. Annual medians were calculated using a uniform subset of the data. Medians are estimations of the data’s central tendency and will be biased towards the portion of the year that is sampled more frequently. Currently, the MCES river monitoring program collects more samples in the warmer months than the colder months. Additionally, the frequency of the sampling protocol has shifted over the 40-years of the dataset. Some years were sampled more often in warmer months (the current protocol); other years were sampled more uniformly; and a handful of years were sampled more often in colder months. To remove these biases, a uniform frequency dataset was subsampled from the full dataset by using the first sample of each month from 1976 to 2015.

Censored Data. Censoring was required in situations where there were gaps in data for part of a year, resulting in a median that was not representative of the full year or comparable to other years. Specifically, the following results were censored from the annual median calculations:

- Minnesota River at Jordan – 1976 – BOD_5, Conductivity, DO, FC, pH, Temperature, TSS
- Minnesota River at Jordan – 1979 – Chl-*a*, NH_3, NO_3, TN, TP
- All sites – 1979 and 1995 – TN
- All sites – 2005 – *E. coli*

Figure 15 shows an example of the NO_3 annual median line from the Mississippi River at Anoka superimposed over the actual data points. In the “Results” section, the annual median lines from each site are plotted together by river.

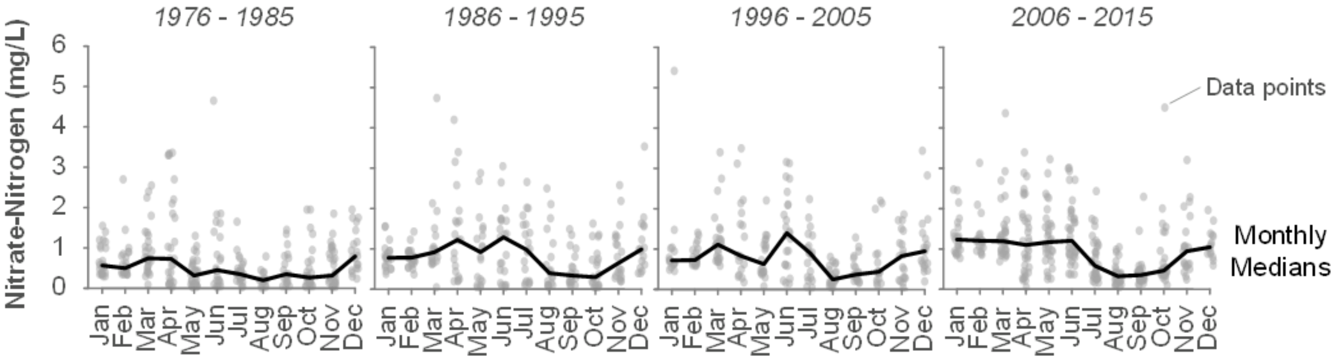
Figure 15. Annual Nitrate-Nitrogen Medians in the Mississippi River at Anoka, with Data Points



Monthly medians at each site were calculated to explore seasonal patterns. Since water quality may have changed over the 40 years of the dataset, the monthly median calculations were divided by decade: 1976-1985, 1986-1995, 1996-2005, and 2006-2015. Subsampling a uniform dataset was not necessary since any bias associated with uneven sampling through a year is not an issue when the data is separated into months.

Figure 16 shows an example of the NO_3 monthly median lines from the Mississippi River at Anoka superimposed over the actual data points. In the “Results” section, the monthly median lines from each site are plotted together by river.

Figure 16. Monthly Nitrate-Nitrogen Medians in the Mississippi River at Anoka, with Data Points



QWTREND Analysis

Trends in water quality can be affected by both natural processes (such as temperature, precipitation, and flow conditions) and human activities (such as urbanization, agricultural practices, and pollution control actions). Implementation of urban and agricultural BMPs and innovative wastewater treatment technologies can reduce nonpoint and point source pollution loads and improve water quality in receiving waters. However, those efforts can also be offset by increases in watershed runoff and stream flow due to seasonal, annual, and long-term climate changes. Therefore, it is important to consider these factors when analyzing water quality trends.

There are two types of water quality trends: non-flow-adjusted and flow-adjusted (Sprague, et al. 2006). The non-flow-adjusted trends are the overall changes in water quality resulting from both natural and human factors. On the other hand, flow-adjusted trends are those analyzed statistically under smoothed flow conditions by removing annual and seasonal variations in flow. While non-flow-adjusted trends provide the status of actual river conditions, the flow-adjusted trends allow identification of water quality trends without the effects of flow variation and water volume on concentrations. The flow-adjusted trends indicate the influence of pollutant sources, pollution control efforts, and other factors on water quality over time. As a side note, concentration trends may differ from load trends, but assessment of load trends was not within the scope of this report.

QWTREND is a statistical program developed by USGS to analyze long-term water quality trends with adjusted flow (Vecchia, 2005). The program is a statistical parametric time-series model that accounts for seasonality, complex flow-related variability, and complex serial correlation structure to detect trends in flow-adjusted concentrations. The QWTREND model can be expressed as (MPCA, 2013):

$$\mathit{Log\ C(t) = Intercept + Time\ Series + Long\ Term + Intermediate\ Term + Seasonal + Trend + HFV}$$

where

Log C(t)	is the log-transformed concentration
Intercept	is the intercept term
Time Series	is the collection of autoregressive and moving-average time-series relations between stream-flow and concentration and within the concentration data
Long Term	is the 5-year anomaly (5-year moving average of log stream flow)
Intermediate Term	is the 1-year and seasonal (3-month) anomaly
Seasonal	is the first- and second-order Fourier terms that describe seasonal variation
Trend	is the user-supplied trend terms that explain long-term deviations not described by the previous terms, and
HFV	is the high-frequency variability in the stream-flow, which is the daily stream flow after the long- and intermediate-term anomalies have been removed

To analyze a long-term water quality trend using QWTREND, the following minimum data are required (Vecchia, 2000):

- At least 15 years of water quality records
- At least 4 samples per year on average
- At least 10 samples within each calendar quarter during the 15-year period
- Less than 10% censored data (that is, non-detections)
- Complete daily flow record for the water quality record during the period of interest, plus the preceding five years

The version of QWTREND used in this study is coded with R, a free public software environment for statistical computing and graphic analysis (R Core Team, 2013). QWTREND, along with R, was used to identify and assess water quality trends for the Mississippi, Minnesota, and St. Croix rivers within the metro area.

To determine a trend for a specific parameter using QWTREND, a trend model needs to be determined first. The trend model is the combined trend pattern that could include either one or multiple sub-trends chosen based on the changes in flow-adjusted concentrations from the initial run of QWTREND.

Determining a trend model and a sub-trend depends on their statistical significances, which are assessed according to the following statistical indexes:

- Akaike Information Criteria (AIC)
- p value
- z score

AIC provides a relative measure of the goodness-of-fit of the statistical trend model to measured concentrations. The p value, or the calculated probability, is used to test statistical significance of a trend model or a sub-trend. The z score, or the measure of standard deviation, is used to estimate the approximate p value of a sub-trend. A statistically significant trend model exists when

$AIC_{model} < AIC_{initial}$, and

$p_{model} < p_{critical}$

where AIC_{model} and $AIC_{initial}$ are the AIC numbers from QWTREND for the model runs with and without sub-trend information, respectively. p_{model} is the p value calculated using QWTREND likelihood for the chosen trend model, and $p_{critical}$ is the critical p value.

There may be several trend models (with one trend or more combined sub-trends) that meet the statistically significant conditions for a parameter. In this study, the trend model that had the lowest p value but simplest trend combination was selected. After a trend model is determined, the approximate sub-trend p values are used to test the statistical significance of sub-trends. A statistically significant sub-trend exists when

$p_{trend} < p_{critical}$

where p_{trend} is the approximate p value estimated from QWTREND z-score for the sub-trend, and $p_{critical}$ is the critical p value. The critical p value typically ranges from 0.01 for a more conservative assessment to 0.1 for a general assessment, depending on study goals, scopes and characteristics of the streams and rivers (MPCA, 2013). In this study, the critical p value for a single trend was set at 0.05 (or the 95% confidence interval). In assessment of statistical significance for trend models, the critical p value was 0.025 calculated at one-half of the one trend-model for a two-trend model, 0.0167 at one-third for a three-trend model and so on (MPCA, 2013).

MCES water quality data and daily flows from USGS and USACE measured in the three metro rivers were used to prepare inputs for QWTREND analysis to analyze river water quality trends. Analysis was performed for nine water quality parameters at each of the 10 river monitoring sites, including six sites on the Mississippi River, two sites on the Minnesota River and another two on the St. Croix River. The selected variables for QWTREND analysis included BOD_5, TSS, TP, NO_3, NH_3, TN, Chl-*a*, FC, and Cl. Based on the data availability of water quality and flow, the trend analysis for the selected parameters were mostly completed for the period of 1976 to 2015 for all river sites except for the following:

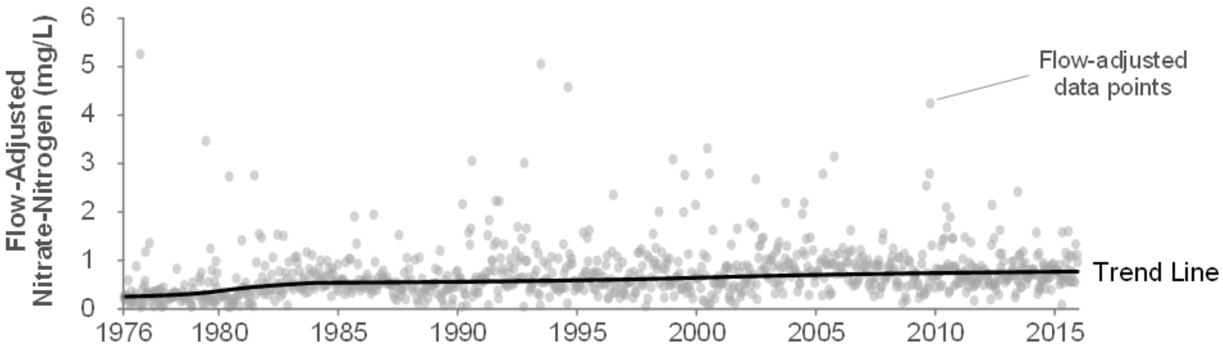
- Cl trends were analyzed from 1985 to 2015 for all river sites
- The trends for the Mississippi River at Grey Cloud Island were analyzed from 1978 to 2015 except for Cl, which was analyzed from 1985 to 2016
- The trends for the Minnesota River at Jordan were analyzed for TP, NO_3, NH_3, and Chl-*a* from 1979 to 2015 and TN from 1980 to 2015

In this report, if a trend model existed and all sub-trends were statistically significant, overall changes of trends in flow-adjusted concentrations were reported for the assessment periods. However, there were three types of situations where overall changes were not reported. The first situation was where a statistically significant trend model did not exist, referred to as “No Trend” (NT). In the second situation, at least one sub-trend within a significant trend model was not statistically significant, referred to as a “Partial Trend” (PT). The third situation occurred when more than 10% of the data were less than the lab’s RL, referred to as “Below Reporting Limit” (BRL).

Even though the overall change could not be calculated for PT and BRL results, the shape and direction of the trends were still reported as an exploratory result to determine if an overall increasing or decreasing trend was apparent (Vecchia, 2017 personal communication). Detailed QWTREND analysis results, including sub-trend periods, changes in flow-adjusted concentrations and rates, p-values, and directions, are listed in the “Appendix: Statistical Analysis of Long-Term Water Quality Trends Using QWTREND”.

Figure 17 shows an example of the NO_3 QWTREND graphical trend result from the Mississippi River at Anoka superimposed over the flow-adjusted concentrations from which it was calculated. In the “Results” section, the QWTREND lines from each site are plotted together by river.

Figure 17. Nitrate-Nitrogen Trend for the Mississippi River at Anoka, with Flow-Adjusted Concentrations



RESULTS

In this section, annual and monthly patterns of 15 water quality parameters show the water quality conditions of 10 sites on the Mississippi, Minnesota, and St. Croix rivers from 1976 to 2015. In this context, a pattern refers to a recognizable form or shape in the data. Annual patterns were created by calculating median concentrations by year from 1976 to 2015. Monthly patterns were created by calculating median concentrations by month in 10-year increments (1976-1985, 1986-1995, 1996-2005, and 2006-2015). The patterns for flow are included in each chart for easy reference alongside the other parameters, since the concentrations of many water quality parameters are affected by flow.

QWTREND was used to calculate trends of nine water quality parameters to show changes in the water quality conditions of the Mississippi, Minnesota, and St. Croix rivers from 1976 to 2015. In this context, “trend” refers to a statistically determined direction of the data over time. QWTREND’s use of flow-adjusted concentrations enable identification of water quality trends with the effects of flow variation and water volume removed. The flow-adjusted concentrations and trends provide a better representation of the effects of anthropogenic activities impacting water quality, such as the influences of pollutant sources and pollution control efforts.

The “Study Methods” section of the report includes detailed information on river sites, water quality parameters, data preparation, and analysis methods. More detailed information on each individual QWTREND result can be found in the “Appendix: Statistical Analysis of Long-Term Water Quality Trends Using QWTREND.”

Mississippi River

Precipitation and Flow

Total annual precipitation at the MSP airport and the Mississippi River annual patterns of median flow and flow volume are presented in Figure 18. Monthly patterns by decade for total precipitation at the MSP airport and for the Mississippi River median flow are presented in Figure 19.

Figure 18. Annual Patterns of Precipitation (MSP Airport) and Mississippi River Median Flows and Flow Volumes, 1976-2015

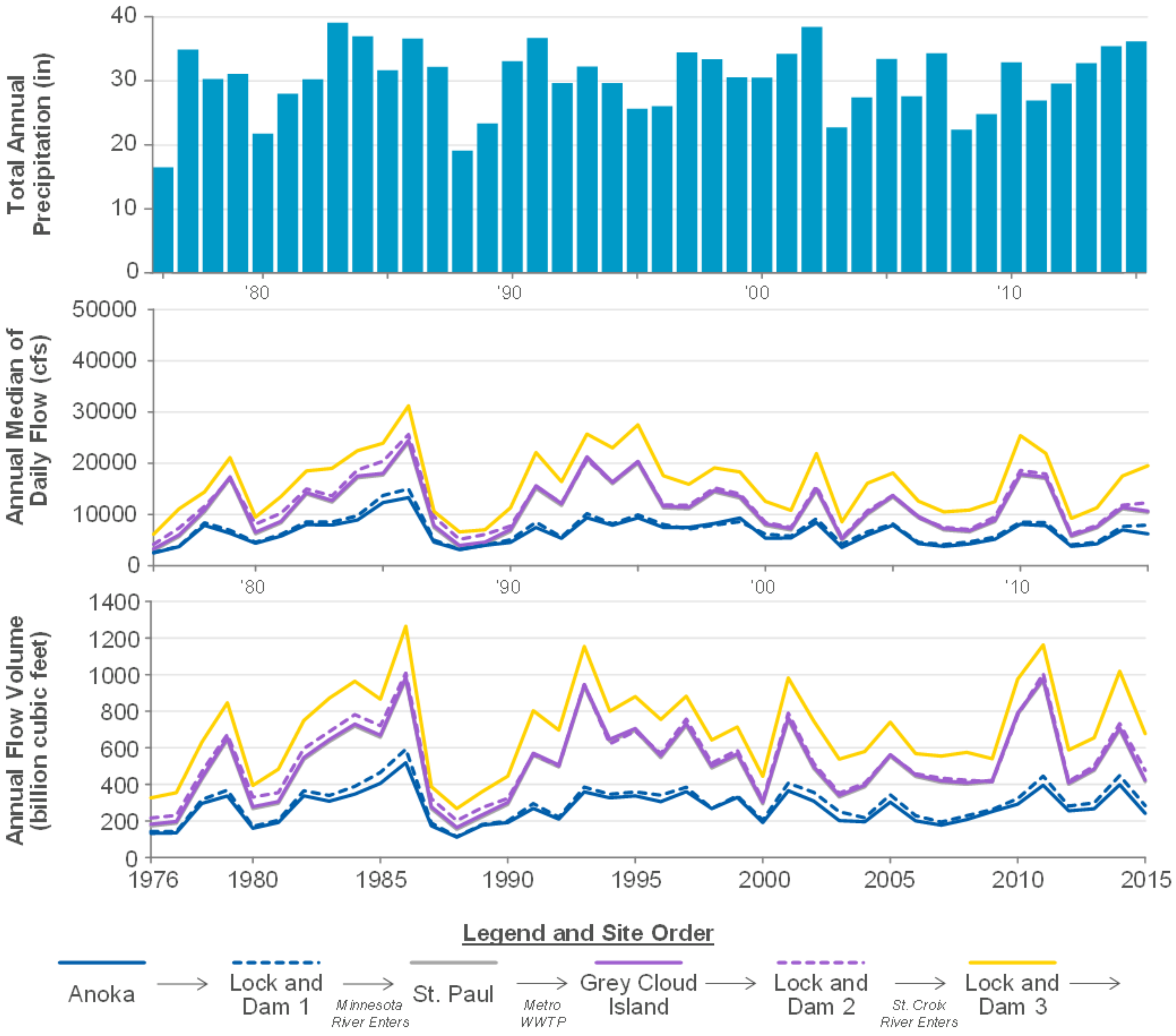
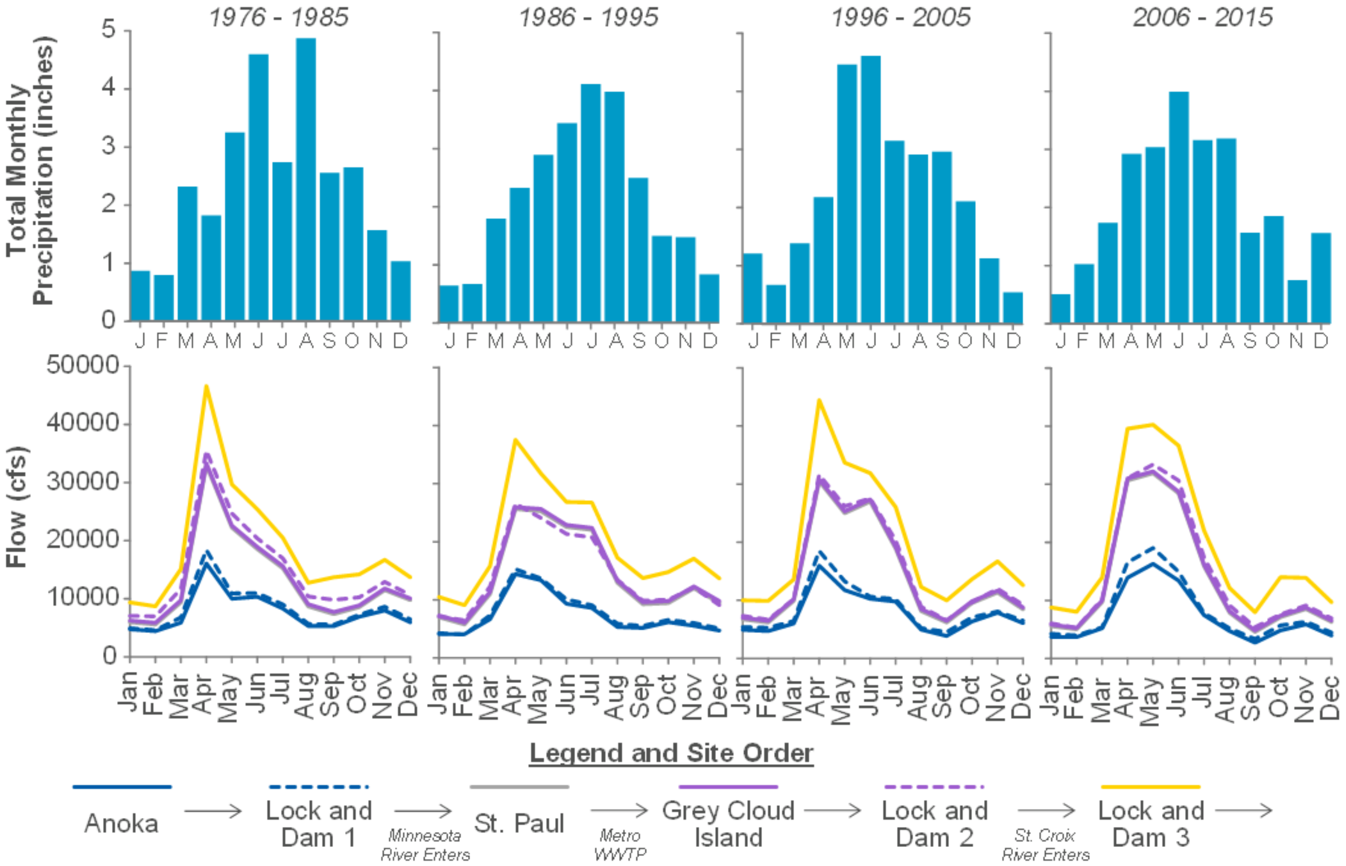


Figure 19. Monthly Patterns of Precipitation (MSP Airport) and Mississippi River Median Flows by Decade, 1976-2015



Dissolved Oxygen (DO) and 5-Day Biochemical Oxygen Demand (BOD_5)

Mississippi River annual patterns for DO and BOD_5 are presented in Figure 20, and monthly patterns by decade are presented in Figure 21. The Mississippi River QWTREND results for BOD_5 are presented in Figure 22. Table 8 lists Mississippi River water quality trends for BOD_5, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 20. Annual Patterns of Mississippi River Median Flows and Concentrations of Dissolved Oxygen and BOD_5, 1976-2015

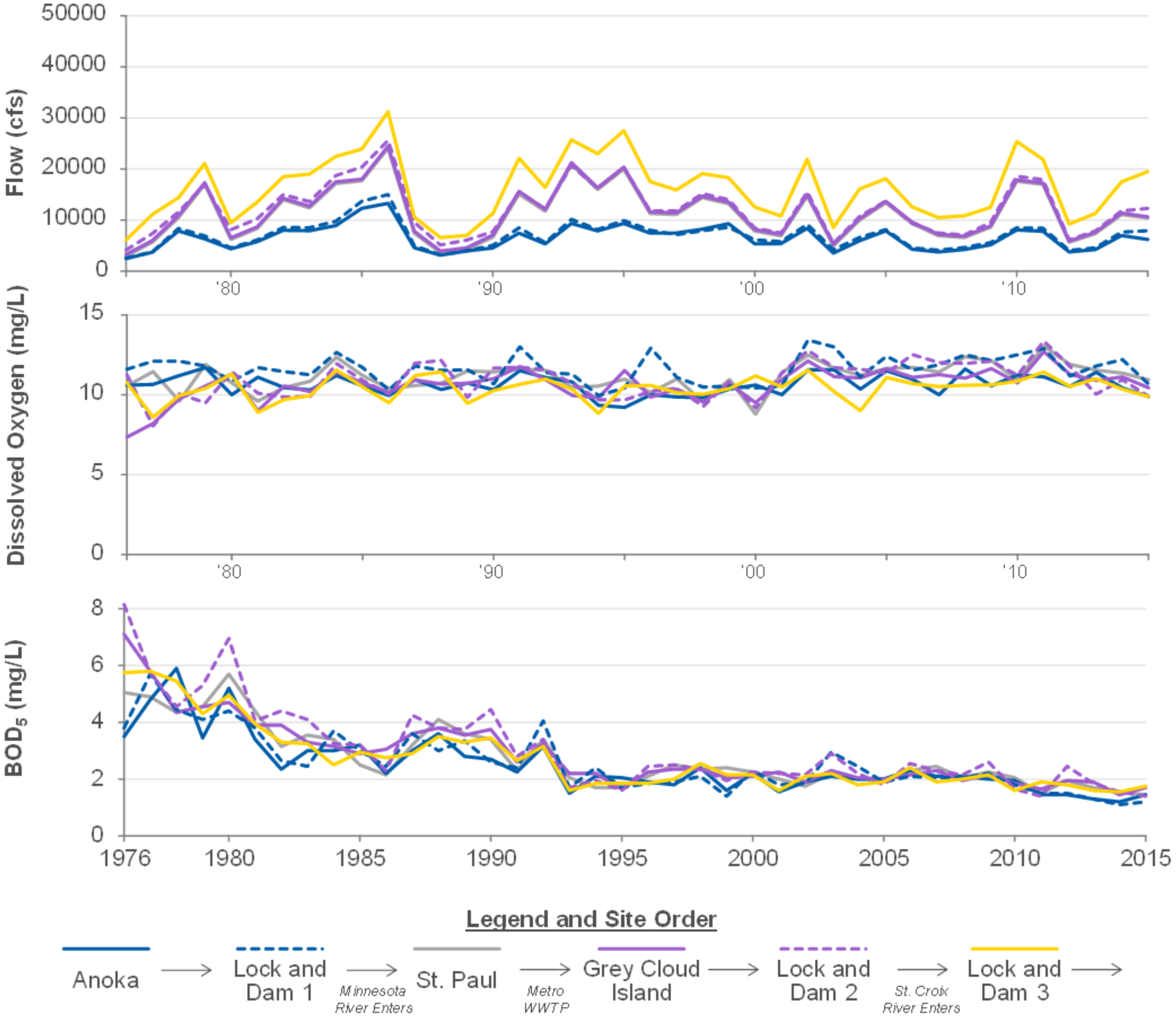


Figure 21. Monthly Patterns of Mississippi River Median Flows and Concentrations of Dissolved Oxygen and BOD_5 by Decade, 1976-2015

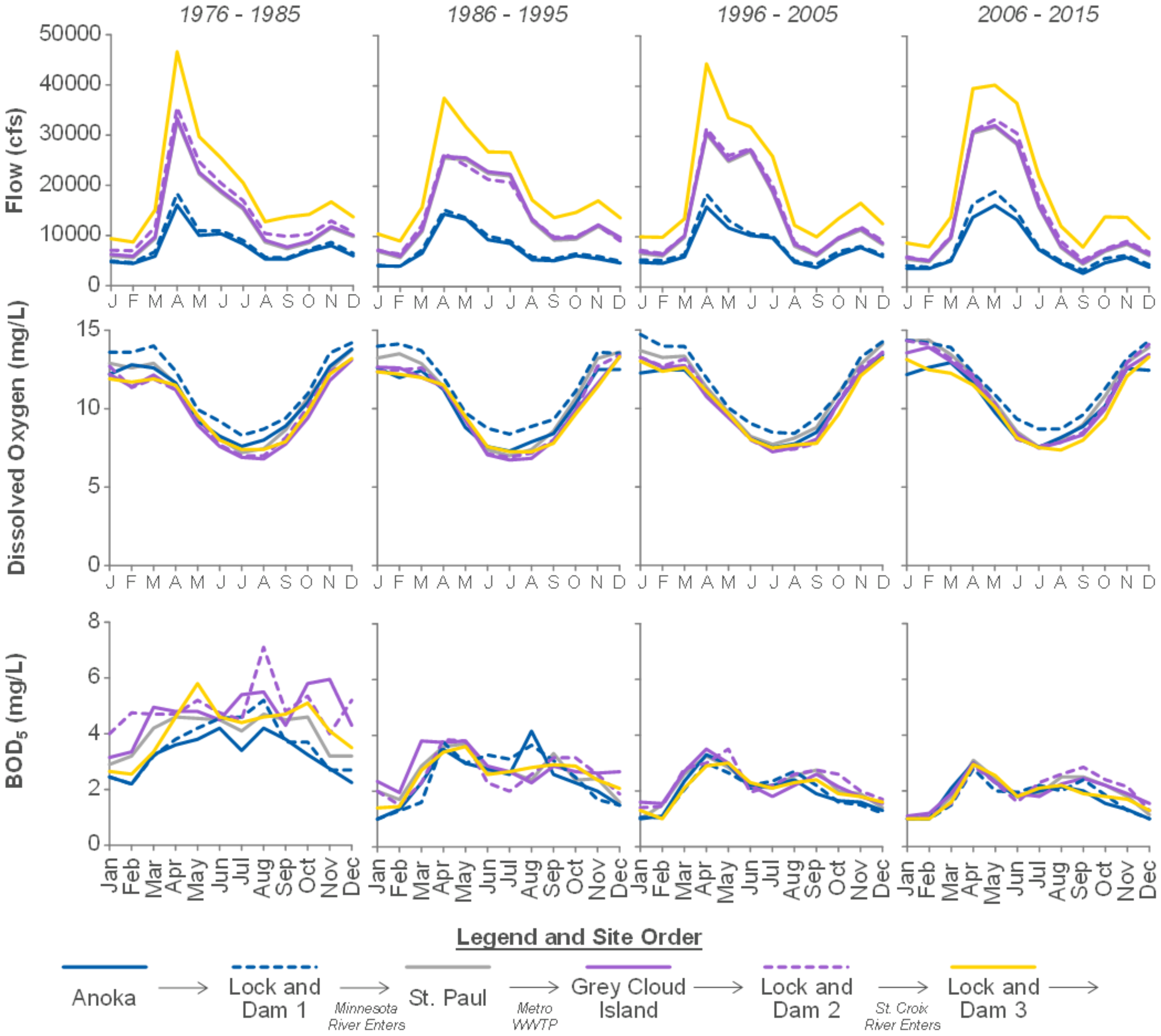


Figure 22. Long-Term Trends of Mississippi River Flow-Adjusted Concentrations of BOD_5, 1976-2015

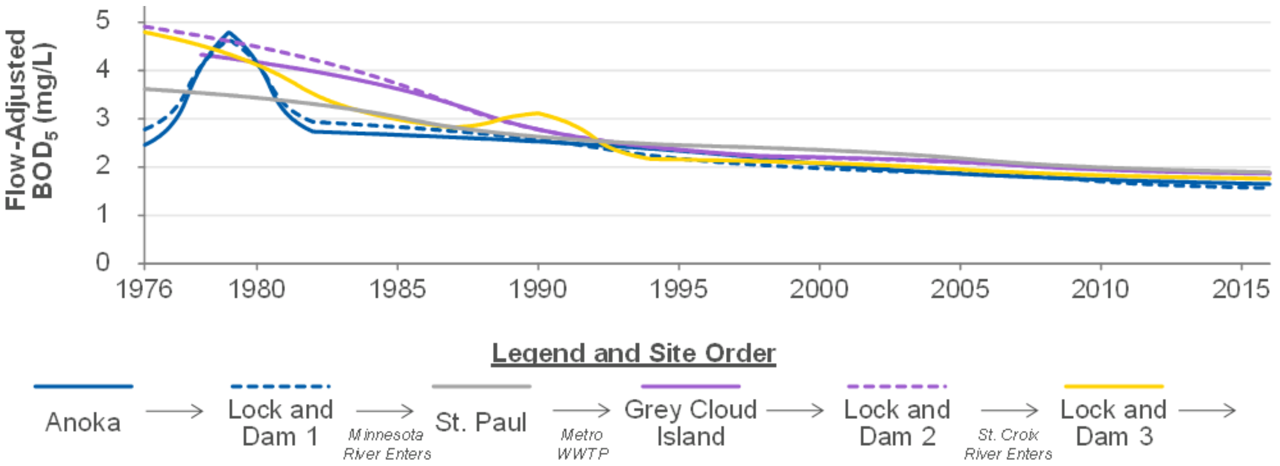


Table 8. Water Quality Trends of Mississippi River Flow-Adjusted Concentrations of BOD_5, 1976-2015*

Site	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End
Anoka	-34	2.5	1.6
Lock and Dam 1	-44	2.8	1.6
Saint Paul	-48	3.6	1.9
Grey Cloud Island	-57	4.3	1.9
Lock and Dam 2	-62	4.9	1.9
Lock and Dam 3	-63	4.8	1.8

* Assessment period at Grey Cloud Island: 1978 to 2015

Temperature, pH, and Conductivity

Mississippi River annual patterns for temperature, pH, and conductivity are presented in Figure 23, and monthly patterns by decade are presented in Figure 24.

Figure 23. Annual Patterns of Mississippi River Median Flows, Temperature, pH, and Conductivity, 1976-2015

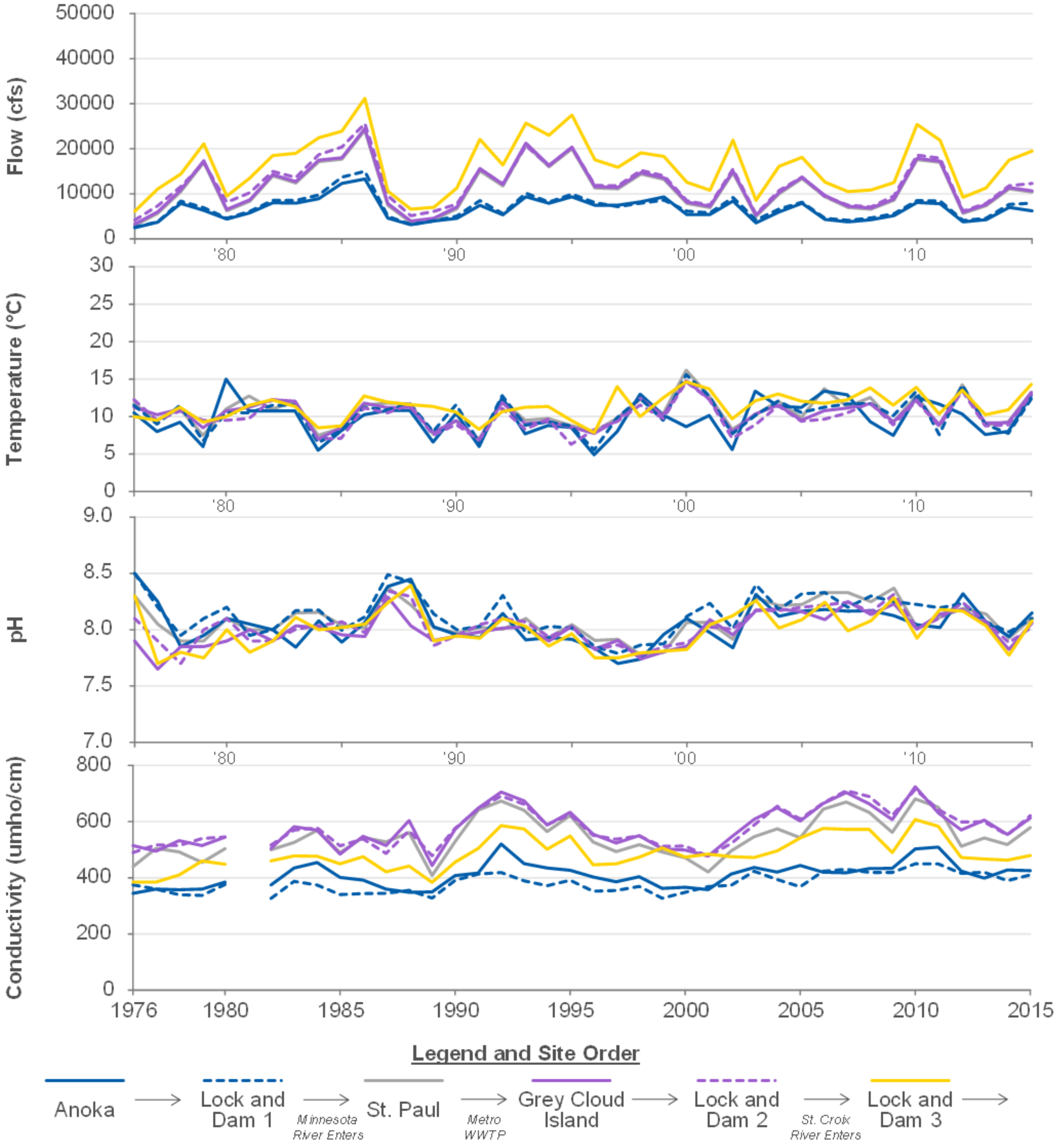
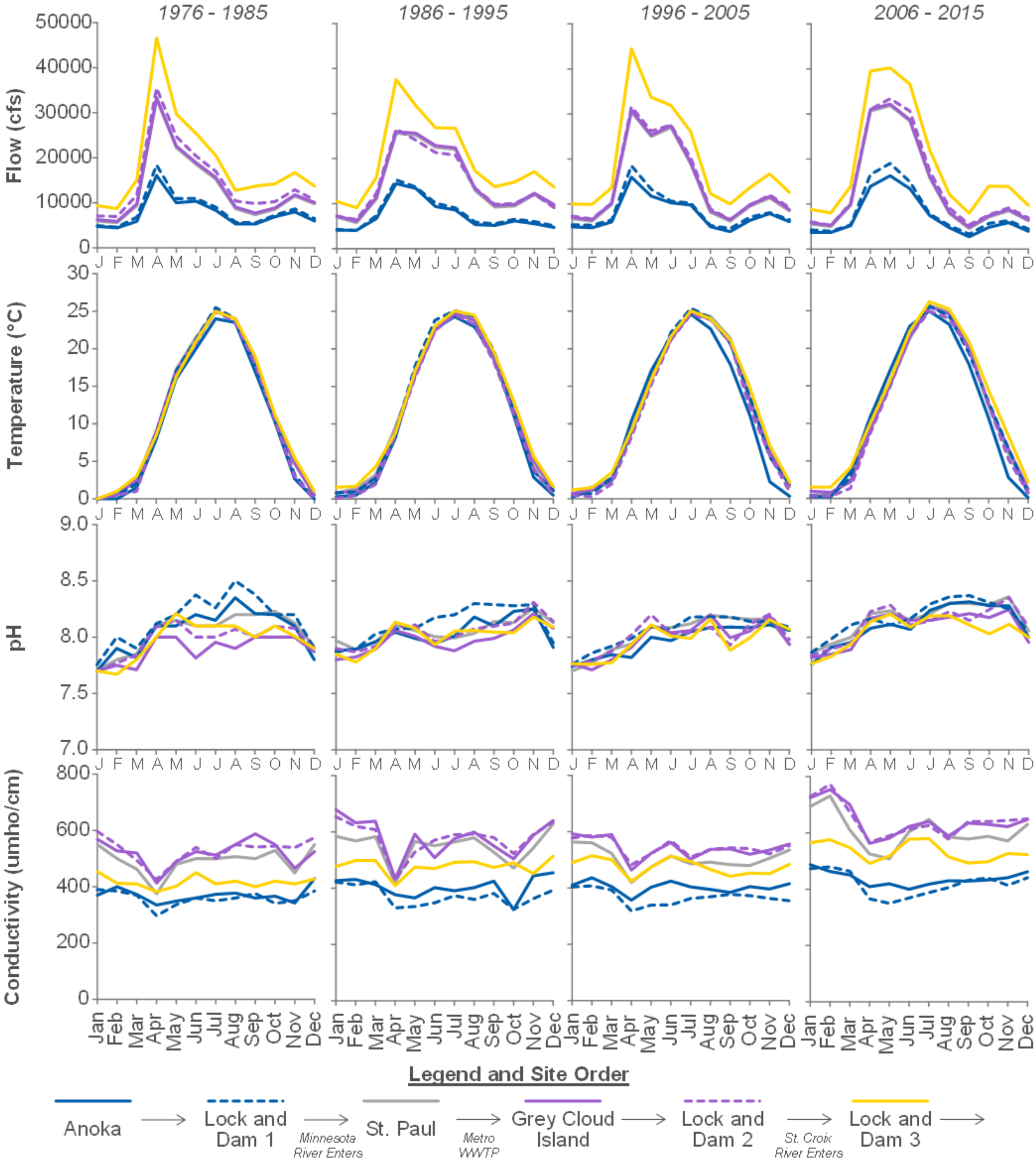


Figure 24. Monthly Patterns of Mississippi River Median Flows, Temperature, pH, and Conductivity by Decade, 1976-2015



Total Suspended Solids (TSS), Total Phosphorus (TP), and Corrected Chlorophyll-*a* (Chl-*a*)

Mississippi River annual patterns for TSS, TP, and Chl-*a* are presented in Figure 25, and the monthly patterns by decade are presented in Figure 26. Mississippi River QWTREND results for TSS, TP, and Chl-*a* are presented in Figure 27. Table 9 lists Mississippi River water quality trends for these three parameters, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 25. Annual Patterns of Mississippi River Median Flows and Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a*, 1976-2015

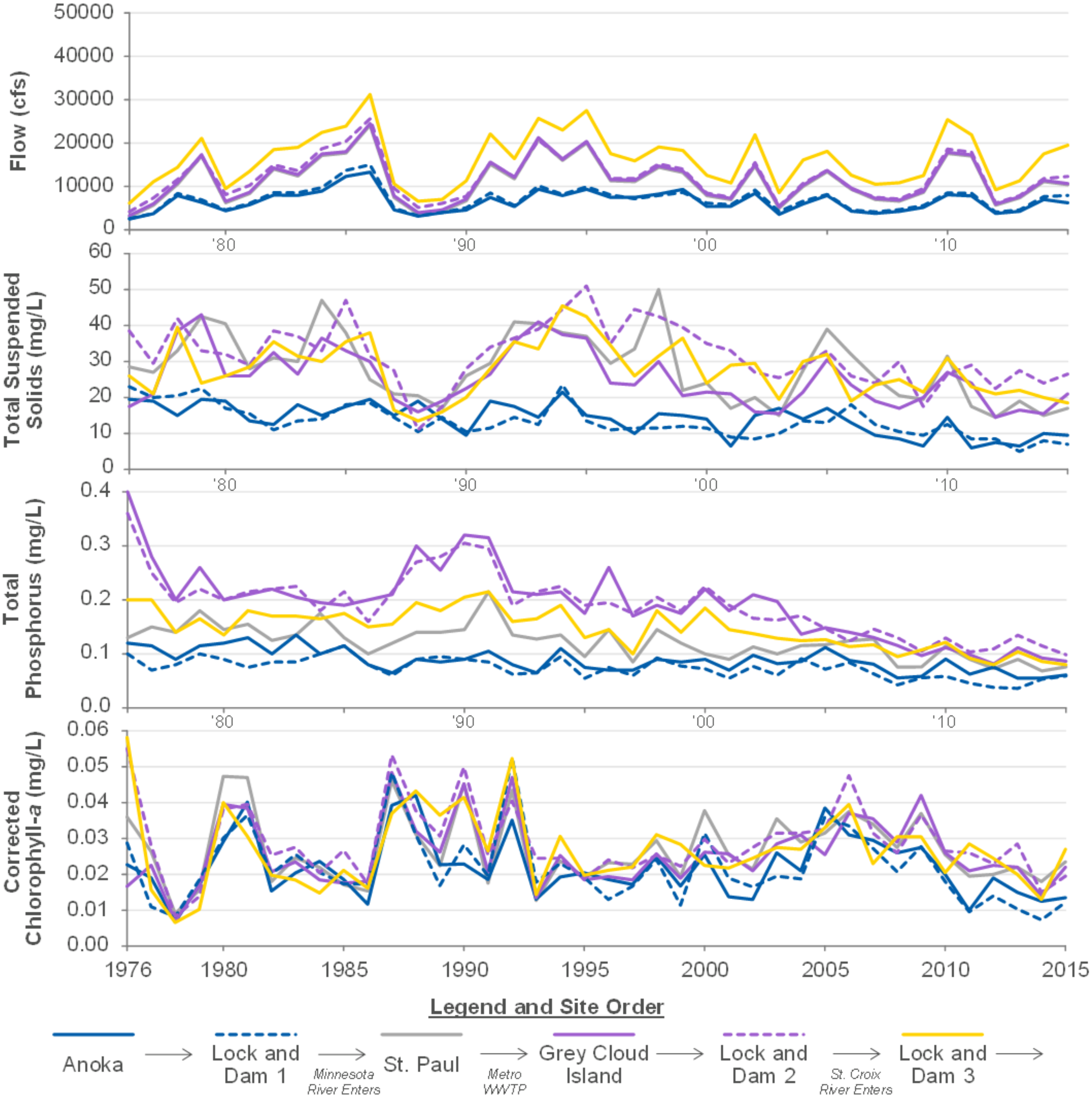


Figure 26. Monthly Patterns of Mississippi River Median Flows and Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a* by Decade, 1976-2015

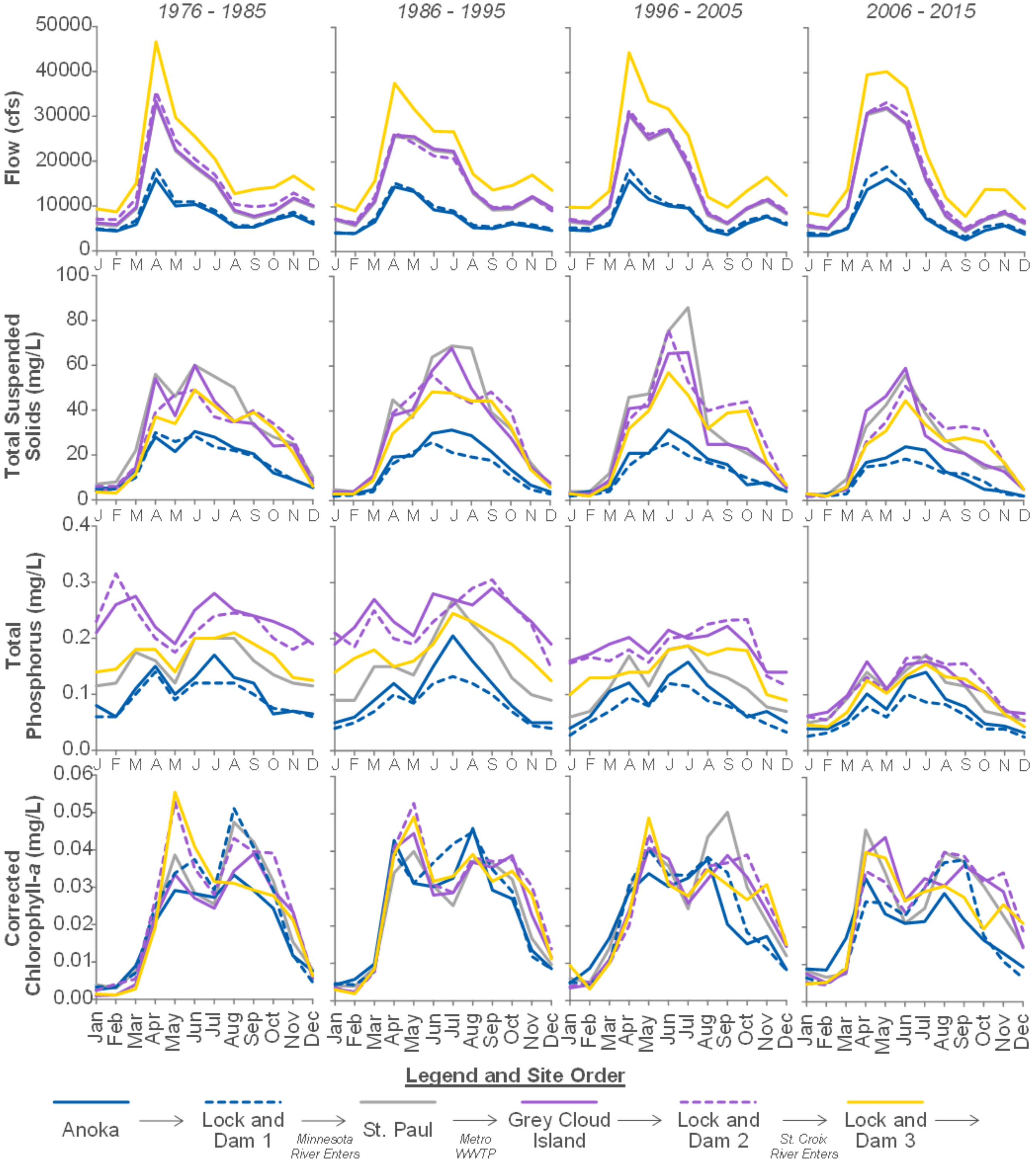


Figure 27. Long-Term Trends of Mississippi River Flow-Adjusted Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a*, 1976-2015

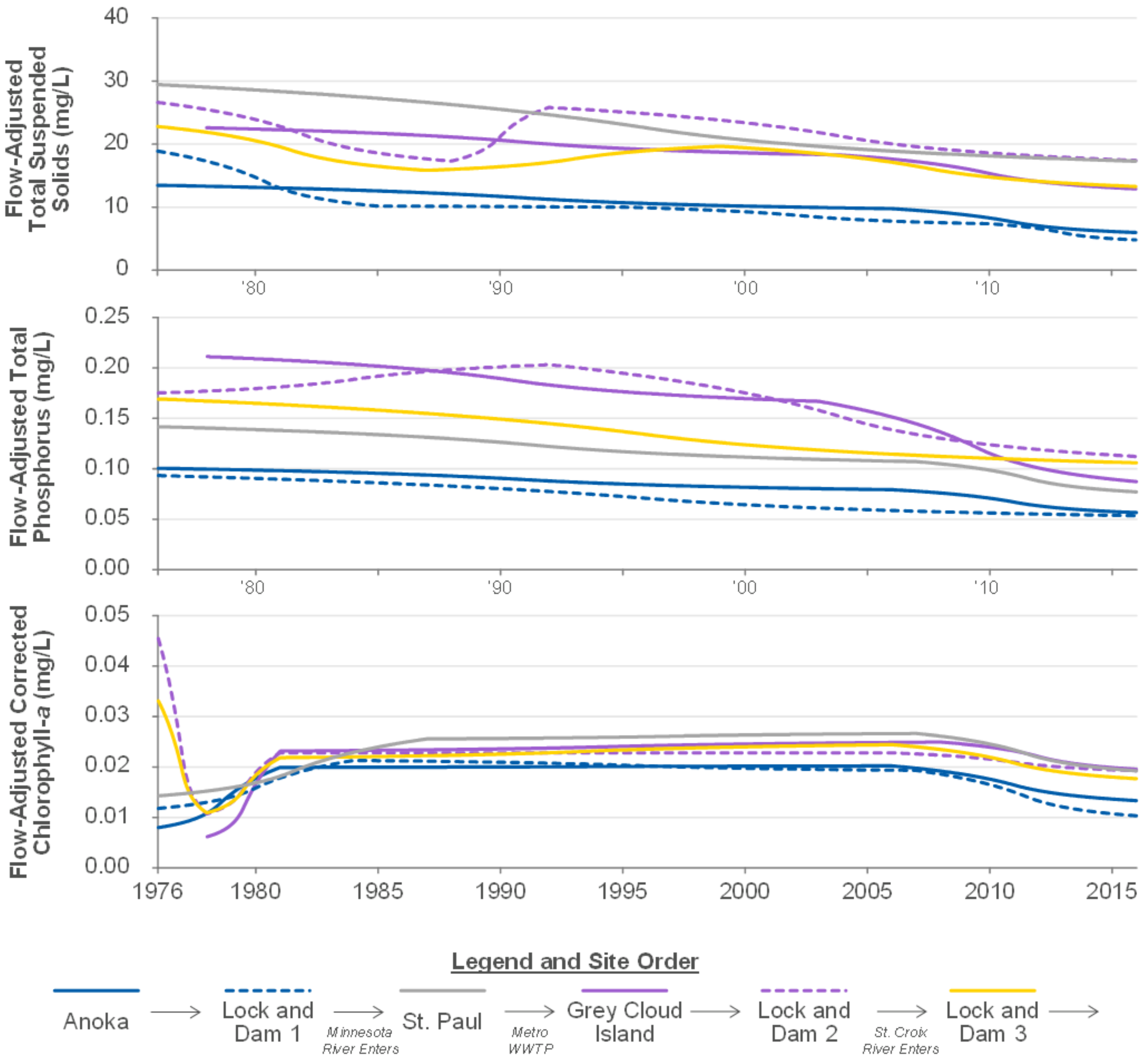


Table 9. Water Quality Trends of Mississippi River Flow-Adjusted Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a*, 1976-2015*

Site	TSS			TP			Chl-*a*		
	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)		Overall Trend (%)	Flow-Adjusted Conc. (mg/L)		Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End		Start	End		Start	End
Anoka	-56	13.4	6.0	-44	0.100	0.057	67	0.008	0.013
Lock and Dam 1	-74	18.9	4.8	-43	0.093	0.053	-12	0.012	0.010
Saint Paul	-41	29.4	17.3	-46	0.142	0.077	34	0.014	0.019
Grey Cloud Island	-43	22.6	12.9	-59	0.211	0.087	217	0.006	0.020
Lock and Dam 2	-34	26.6	17.4	-36	0.174	0.112	PT	-	-
Lock and Dam 3	-42	22.8	13.3	-37	0.169	0.106	-47	0.033	0.018

* Assessment period at Grey Cloud Island: 1978 to 2015.

PT - Partial Trend: One of the sub-trends within the trend model was not statistically significant, so a representative overall percentage change could not be calculated.

Total Nitrogen (TN), Nitrate-Nitrogen (NO_3), and Ammonia-Nitrogen (NH_3)

Mississippi River annual patterns for TN, NO_3, and NH_3 are presented in Figure 28, and monthly patterns by decade are presented in Figure 29. Mississippi River QWTREND results for TN, NO_3, and NH_3 are presented in Figure 30. Table 10 lists Mississippi River water quality trends for TN, NO_3, and NH_3, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 28. Annual Patterns of Mississippi River Median Flows and Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen, 1976-2015

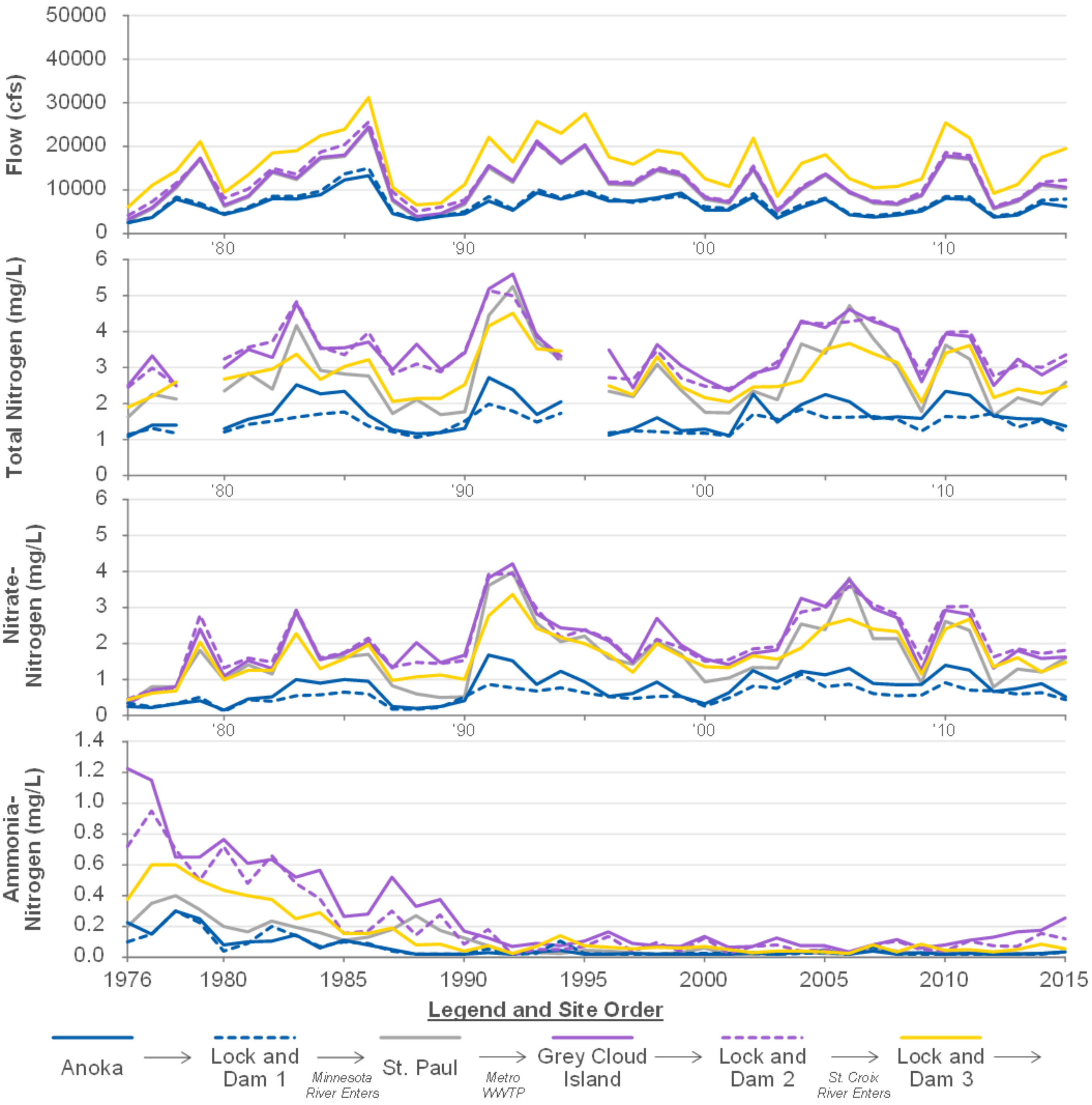


Figure 29. Monthly Patterns of Mississippi River Median Flows and Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen by Decade, 1976-2015

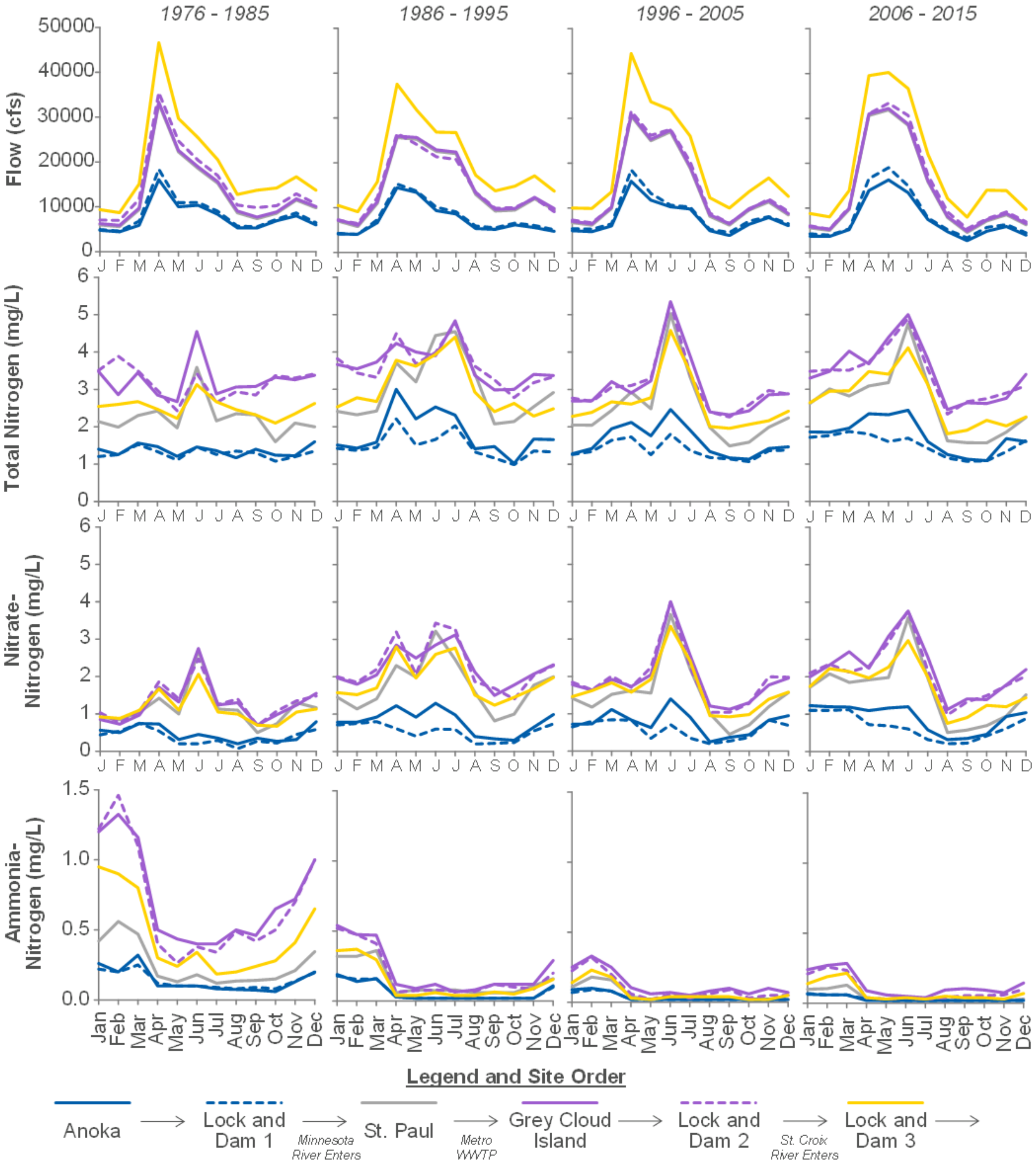


Figure 30. Long-Term Trends of Mississippi River Flow-Adjusted Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen, 1976-2015

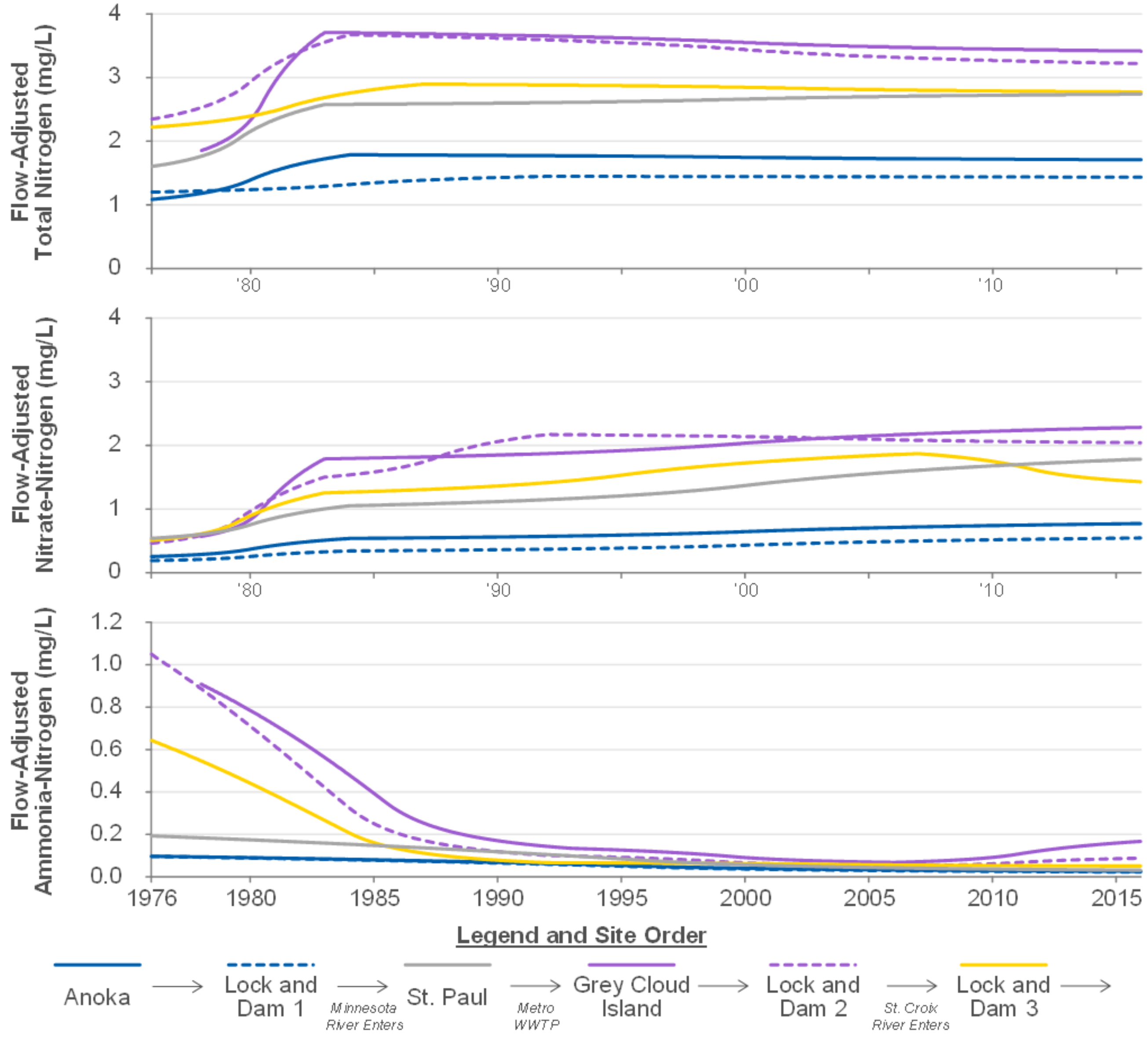


Table 10. Water Quality Trends of Mississippi River Flow-Adjusted Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen, 1976 to 2015*

Site	**TN**			**NO_3**			**NH_3**		
	Overall Trend (%)	**Flow-Adjusted Conc. (mg/L)**		**Overall Trend (%)**	**Flow-Adjusted Conc. (mg/L)**		**Overall Trend (%)**	**Flow-Adjusted Conc. (mg/L)**	
		Start	**End**		**Start**	**End**		**Start**	**End**
Anoka	PT	-	-	204	0.25	0.77	BRL	-	-
Lock and Dam 1	PT	-	-	187	0.19	0.54	BRL	-	-
Saint Paul	PT	-	-	223	0.54	1.78	BRL	-	-
Grey Cloud Island	PT	-	-	302	0.57	2.28	-82	0.908	0.167
Lock and Dam 2	37	2.34	3.22	PT	-	-	BRL	-	-
Lock and Dam 3	PT	-	-	181	0.51	1.43	BRL	-	-

* Assessment period at Grey Cloud Island: 1978 to 2015.

PT - Partial Trend: One of the sub-trends within the trend model was not statistically significant, so a representative overall percentage change could not be calculated.

BRL - Below Reporting Limit: More than 10% of the data were below than the lab's RL, so a representative overall percentage change could not be calculated.

Fecal Coliform (FC) and *Escherichia coli* (*E. coli*) Bacteria

Mississippi River annual patterns for FC and *E. coli* are presented in Figure 31, and monthly patterns by decade are presented in Figure 32. Mississippi River QWTREND results for FC are presented in Figure 33. Table 11 lists Mississippi River water quality trends for FC, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 31. Annual Patterns of Mississippi River Median Flows and Concentrations of Fecal Coliform and *E. coli*, 1976-2015

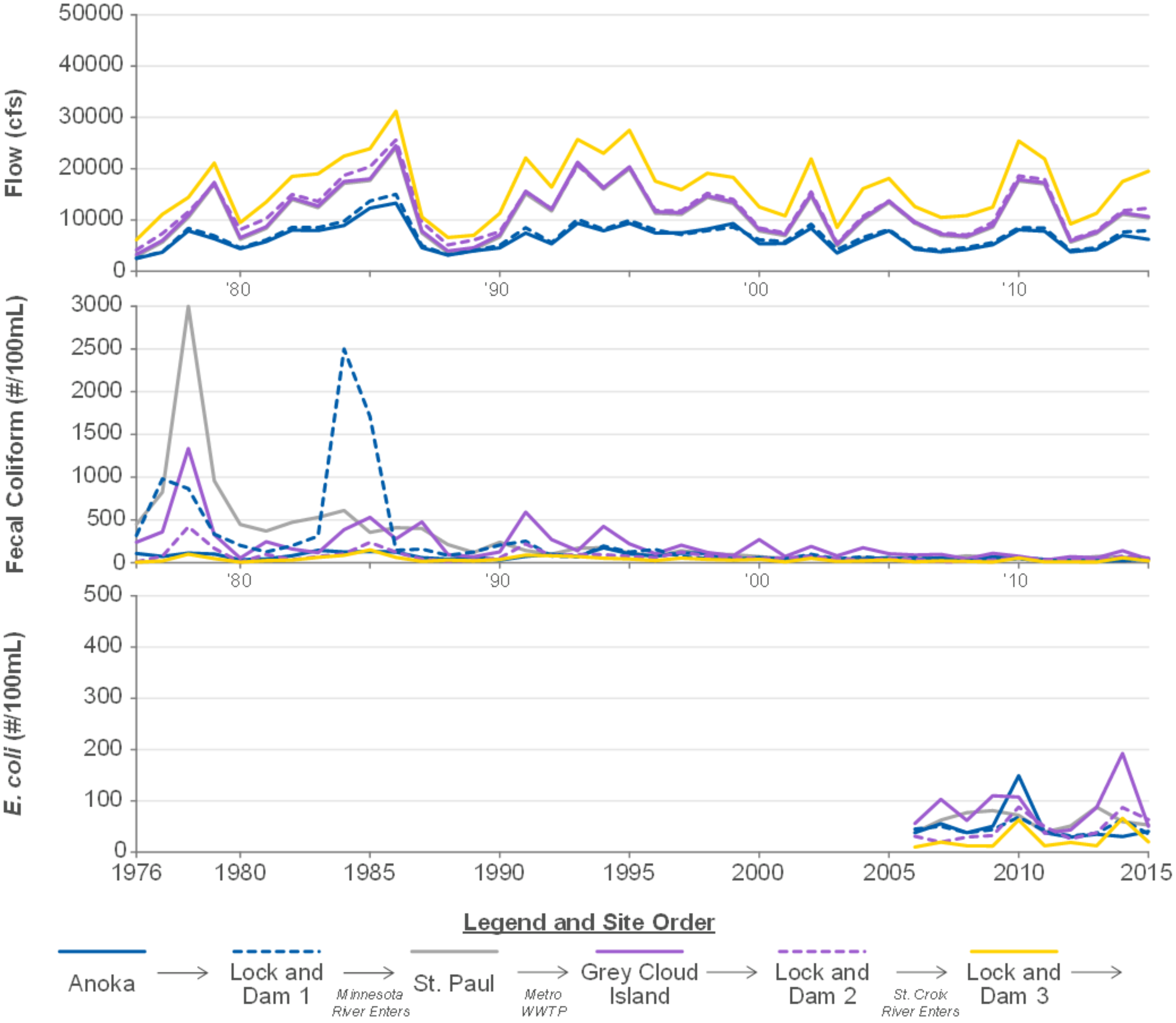


Figure 32. Monthly Patterns of Mississippi River Median Flows and Concentrations of Fecal Coliform and *E. coli* by Decade, 1976-2015

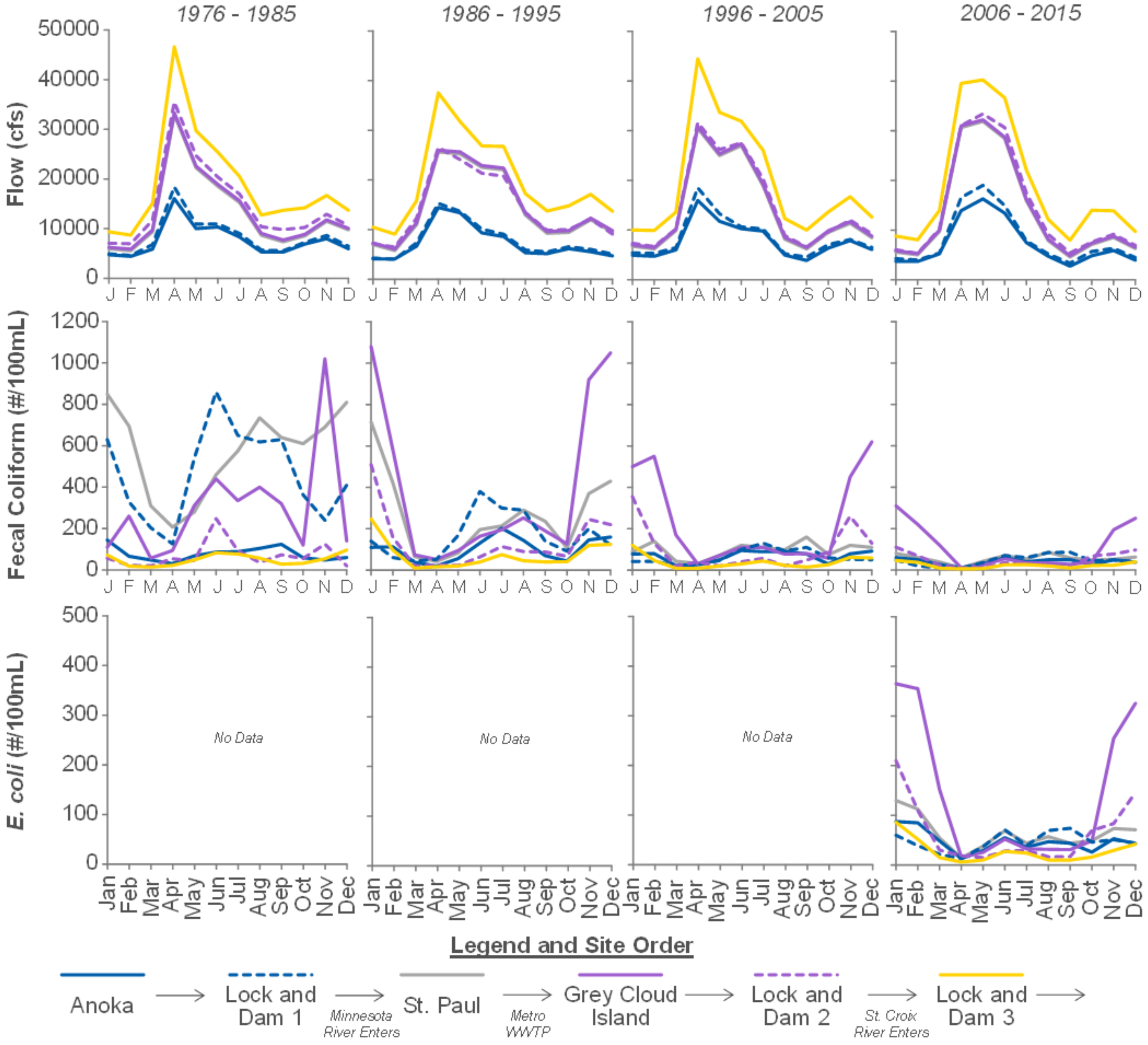


Figure 33. Long-Term Trends of Mississippi River Flow-Adjusted Concentrations of Fecal Coliform, 1976-2015

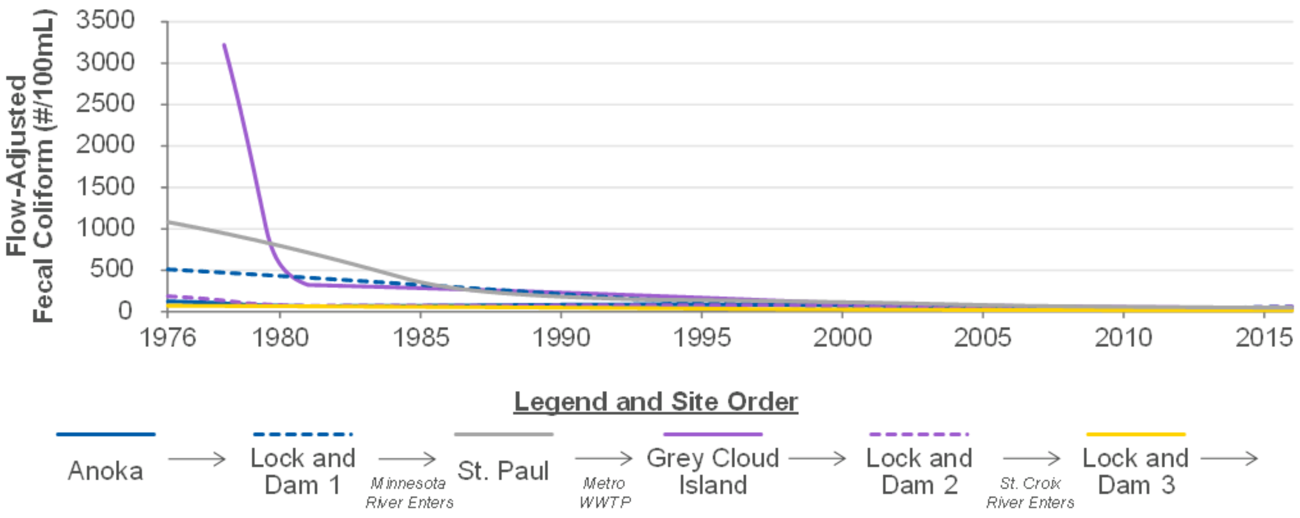


Table 11. Water Quality Trends of Mississippi River Flow-Adjusted Concentrations of Fecal Coliform, 1976-2015*

Site	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	**End**
Anoka	-66	124	42
Lock and Dam 1	PT	-	-
Saint Paul	-96	1084	96
Grey Cloud Island	-98	3236	46
Lock and Dam 2	-67	186	60
Lock and Dam 3	-77	72	16

* Assessment period at Grey Cloud Island: 1978 to 2015.

PT - Partial Trend: One of the sub-trends within the trend model was not statistically significant, so a representative overall percentage change could not be calculated.

Chloride (Cl)

Mississippi River annual patterns for Cl are presented in Figure 34, and monthly patterns by decade are presented in Figure 35. Mississippi River QWTREND results for Cl are presented in Figure 36. Table 12 lists Mississippi River water quality trends for Cl, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 34. Annual Patterns of Mississippi River Median Flows and Chloride Concentrations, 1985-2015

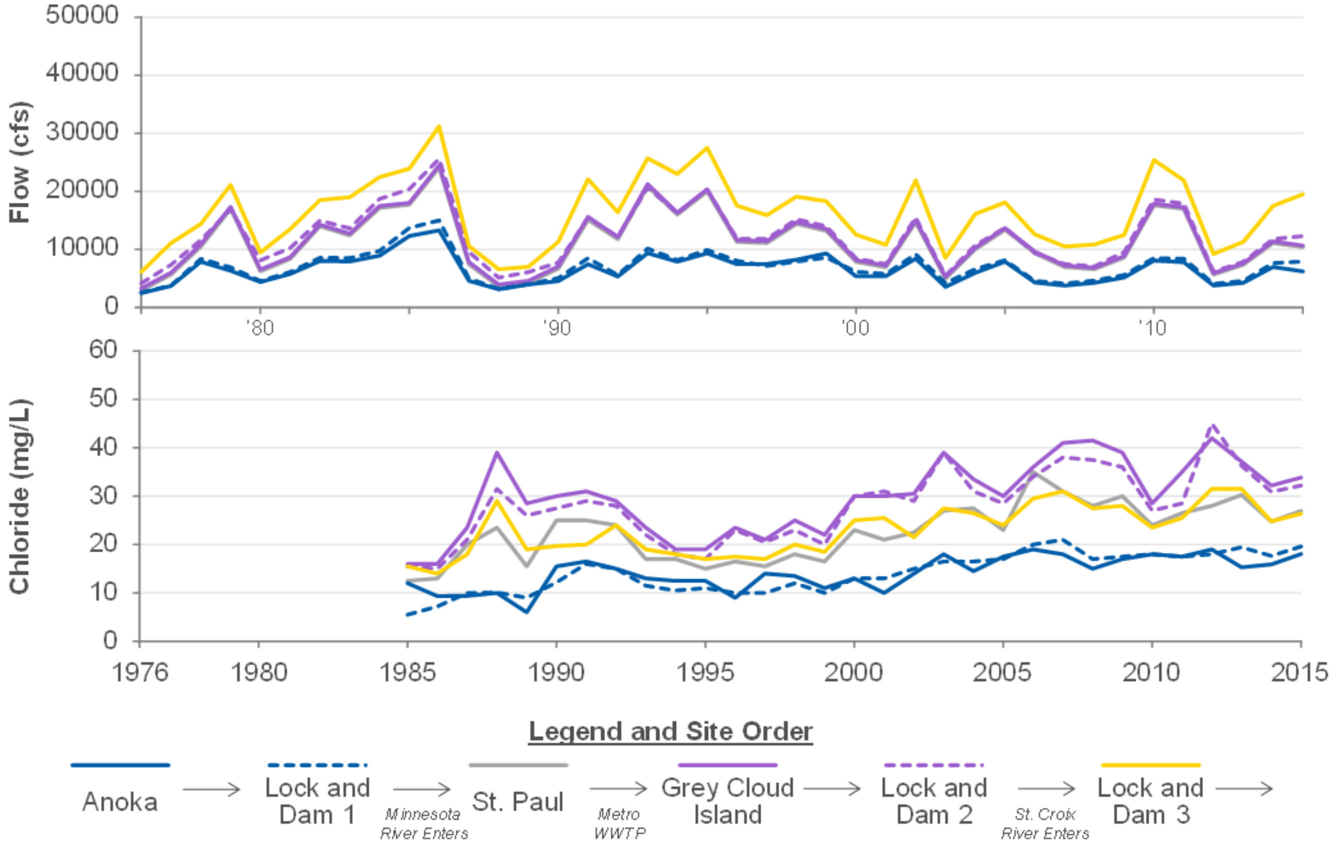


Figure 35. Monthly Patterns of Mississippi River Median Flows and Chloride Concentrations by Decade, 1985-2015

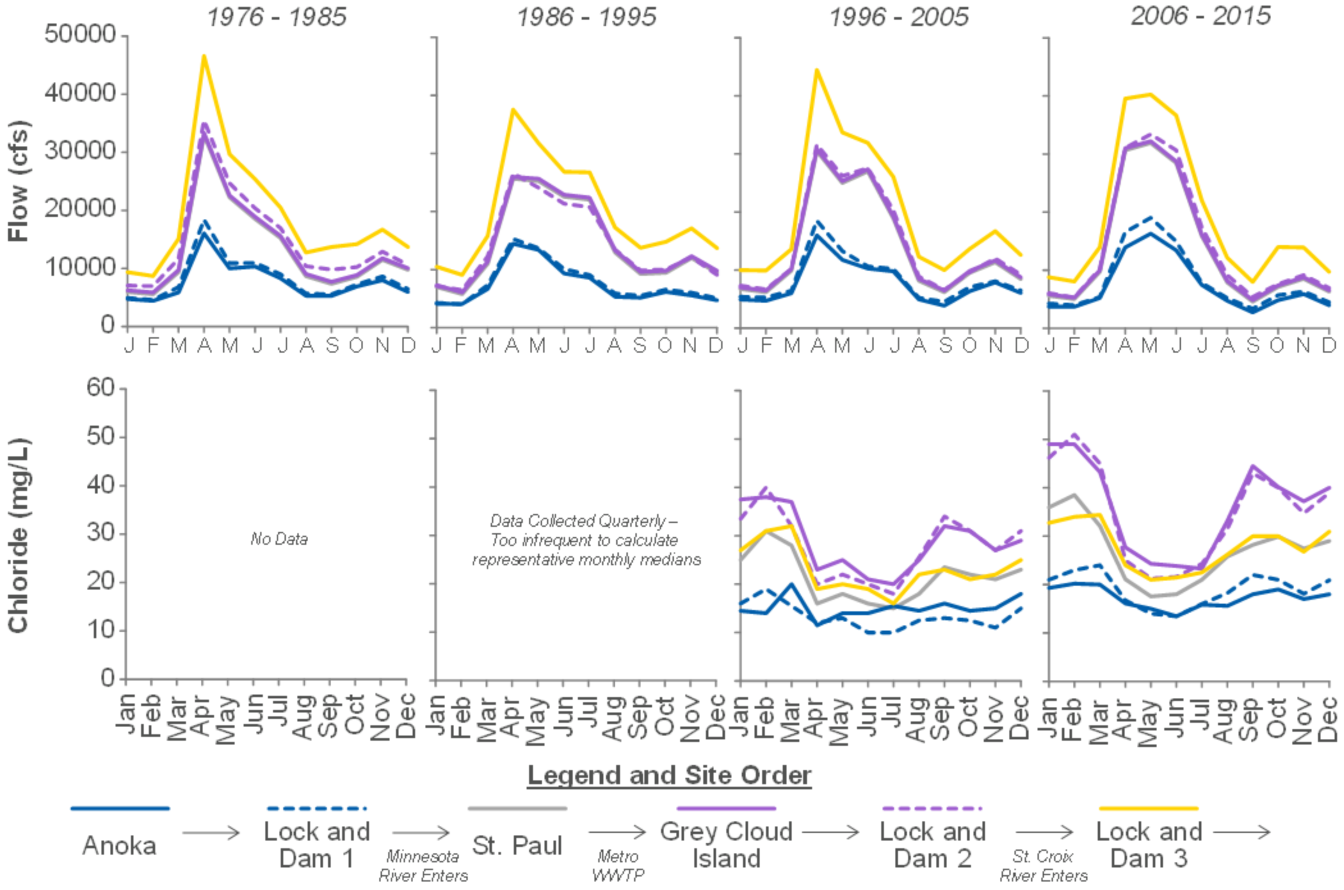


Figure 36. Long-Term Trends of Mississippi River Flow-Adjusted Concentrations of Chloride, 1985-2015

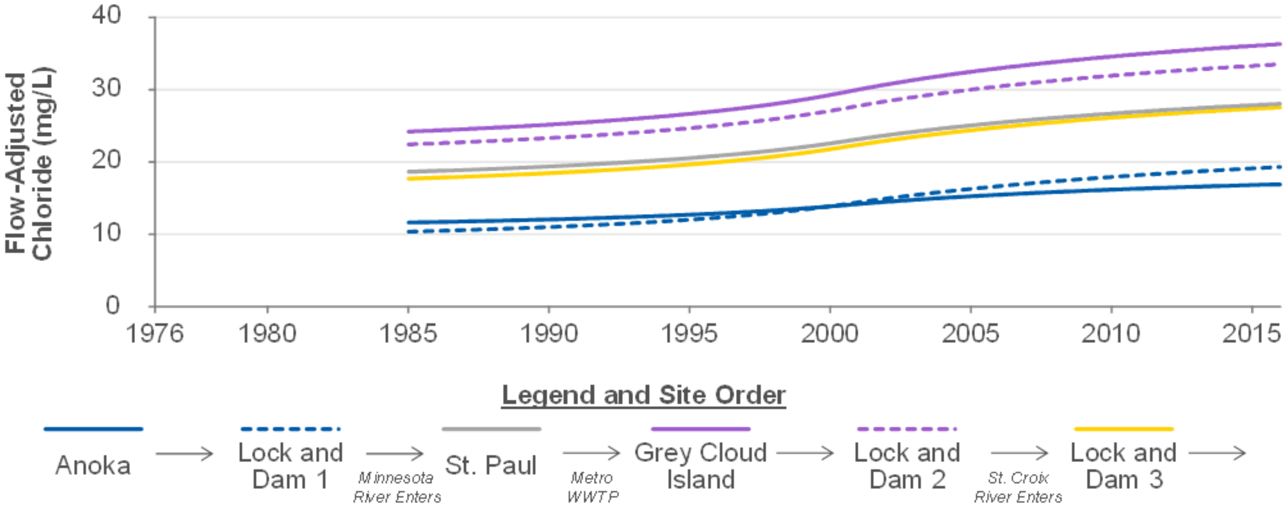


Table 12. Water Quality Trends of Mississippi River Flow-Adjusted Concentrations of Chloride, 1985-2015

Site	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End
Anoka	45	11.6	16.9
Lock and Dam 1	86	10.4	19.3
Saint Paul	50	18.7	28.0
Grey Cloud Island	50	24.2	36.3
Lock and Dam 2	49	22.4	33.5
Lock and Dam 3	56	17.7	27.7

Minnesota River

Precipitation and Flow

Total annual precipitation at the MSP airport and the Minnesota River annual patterns of median flow and flow volume are presented in Figure 37. Monthly patterns by decade for total precipitation at the MSP airport and for the Minnesota River median flow are presented in Figure 38.

Figure 37. Annual Patterns of Precipitation (MSP Airport) and Minnesota River Median Flows and Flow Volumes, 1976-2015

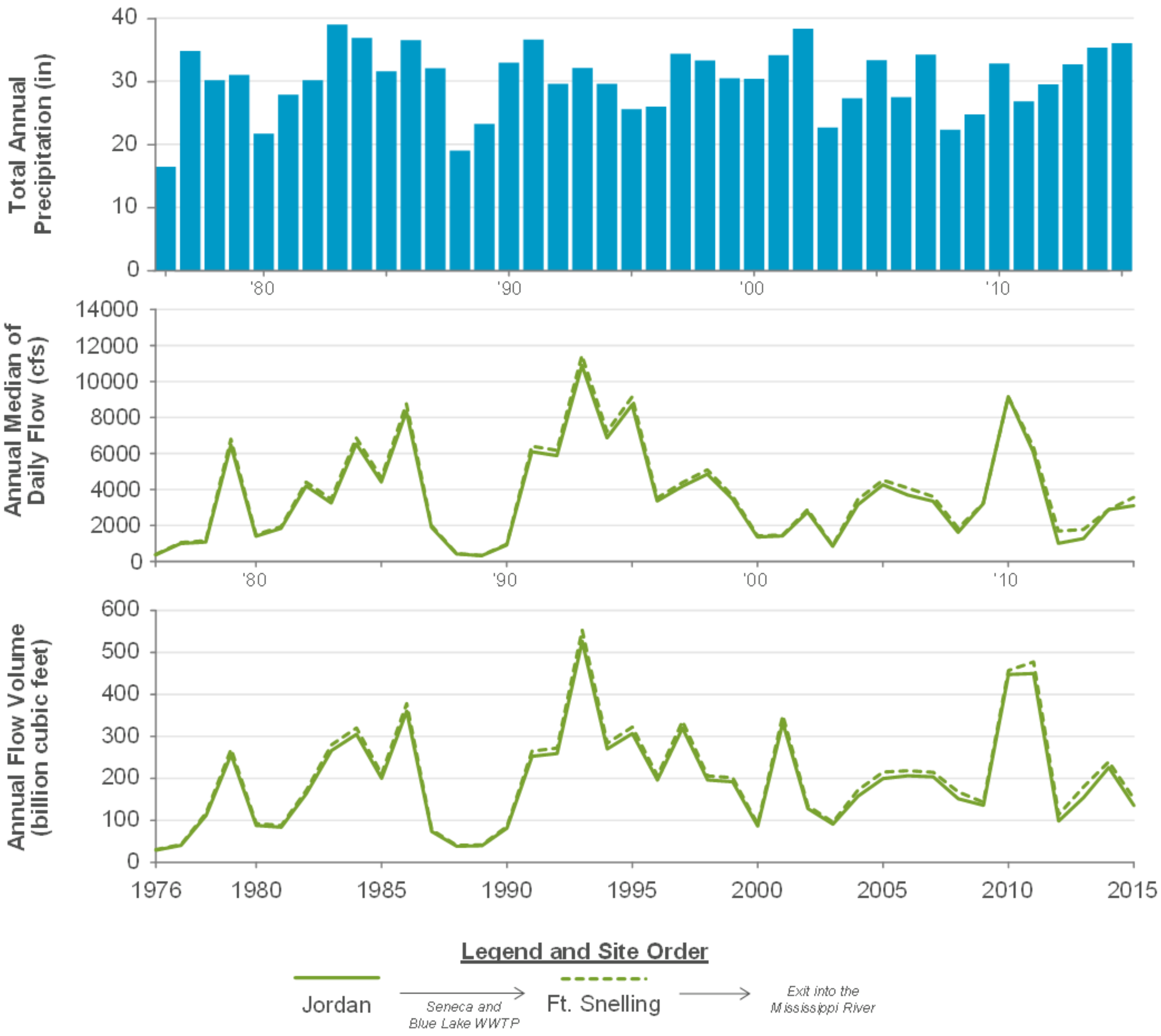
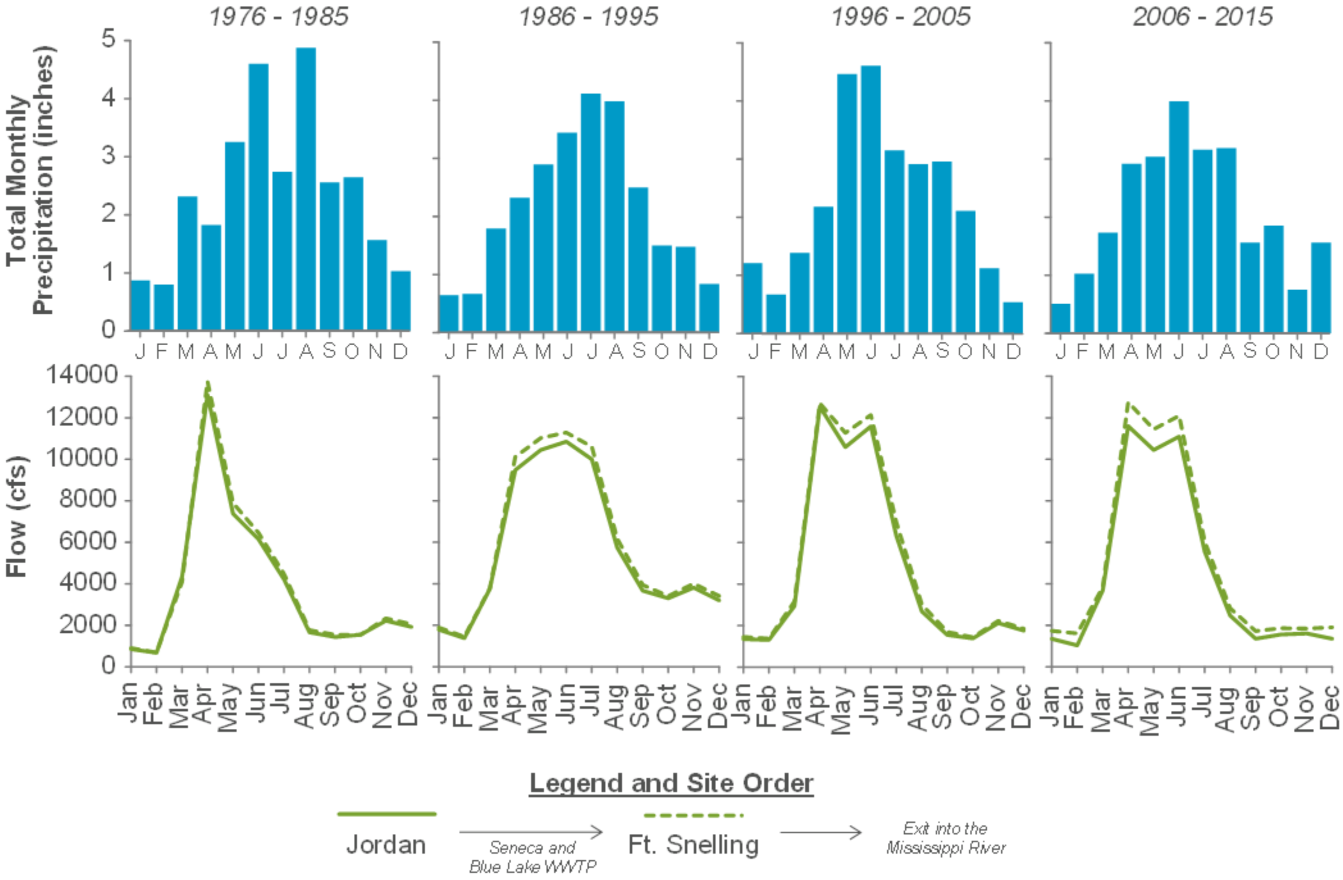


Figure 38. Monthly Patterns of Precipitation (MSP Airport) and Median Minnesota River Flows by Decade, 1976-2015



Dissolved Oxygen (DO) and 5-Day Biochemical Oxygen Demand (BOD_5)

Minnesota River annual patterns for DO and BOD_5 are presented in Figure 39, and monthly patterns by decade are presented in Figure 40. The Minnesota River QWTREND results for BOD5 are presented in Figure 41. Table 13 lists Minnesota River water quality trends for BOD_5, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 39. Annual Patterns of Minnesota River Median Flows and Concentrations of Dissolved Oxygen and BOD_5, 1976-2015

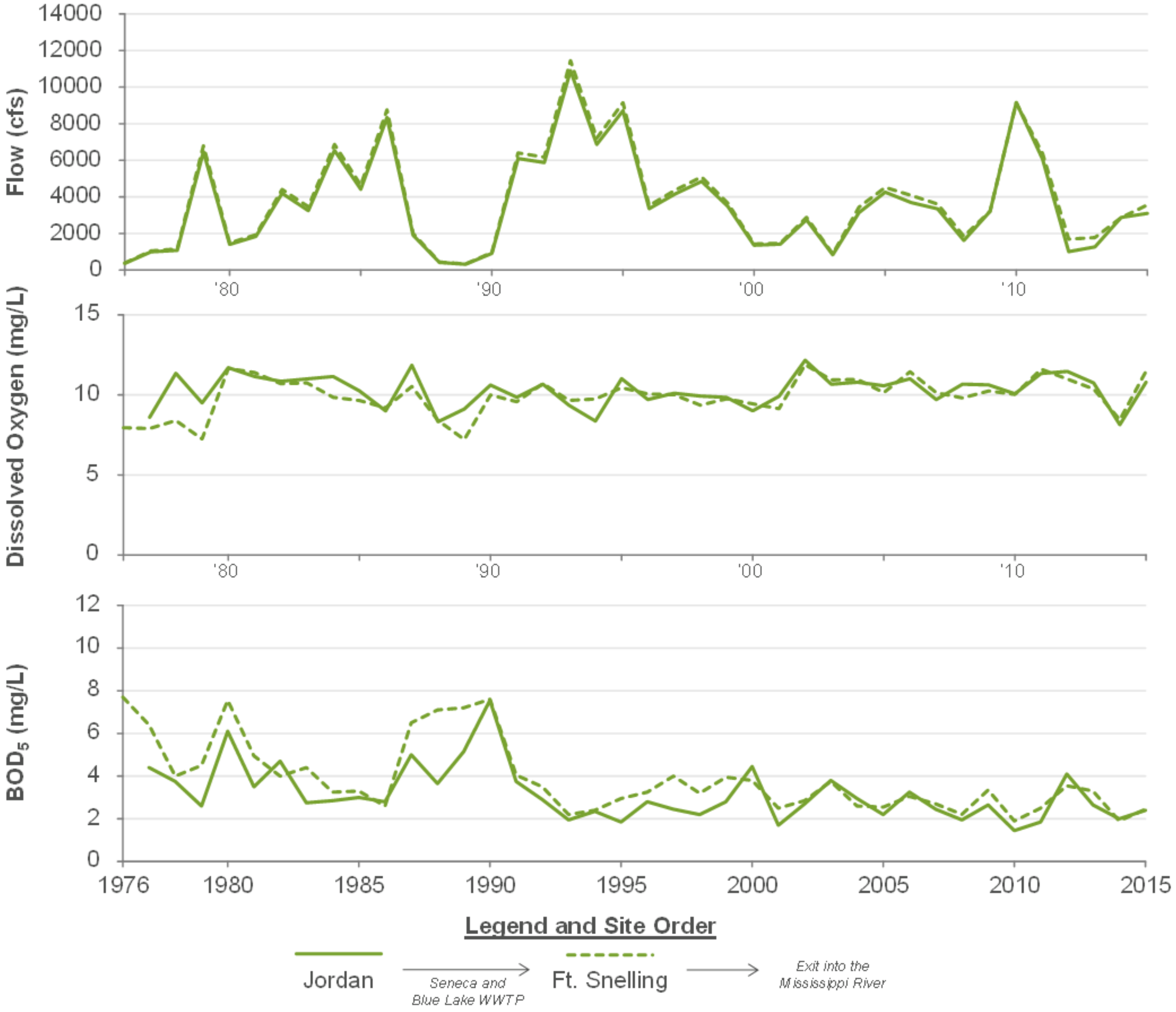


Figure 40. Monthly Patterns of Minnesota River Median Flows and Concentrations of Dissolved Oxygen and BOD_5 by Decade, 1976-2015

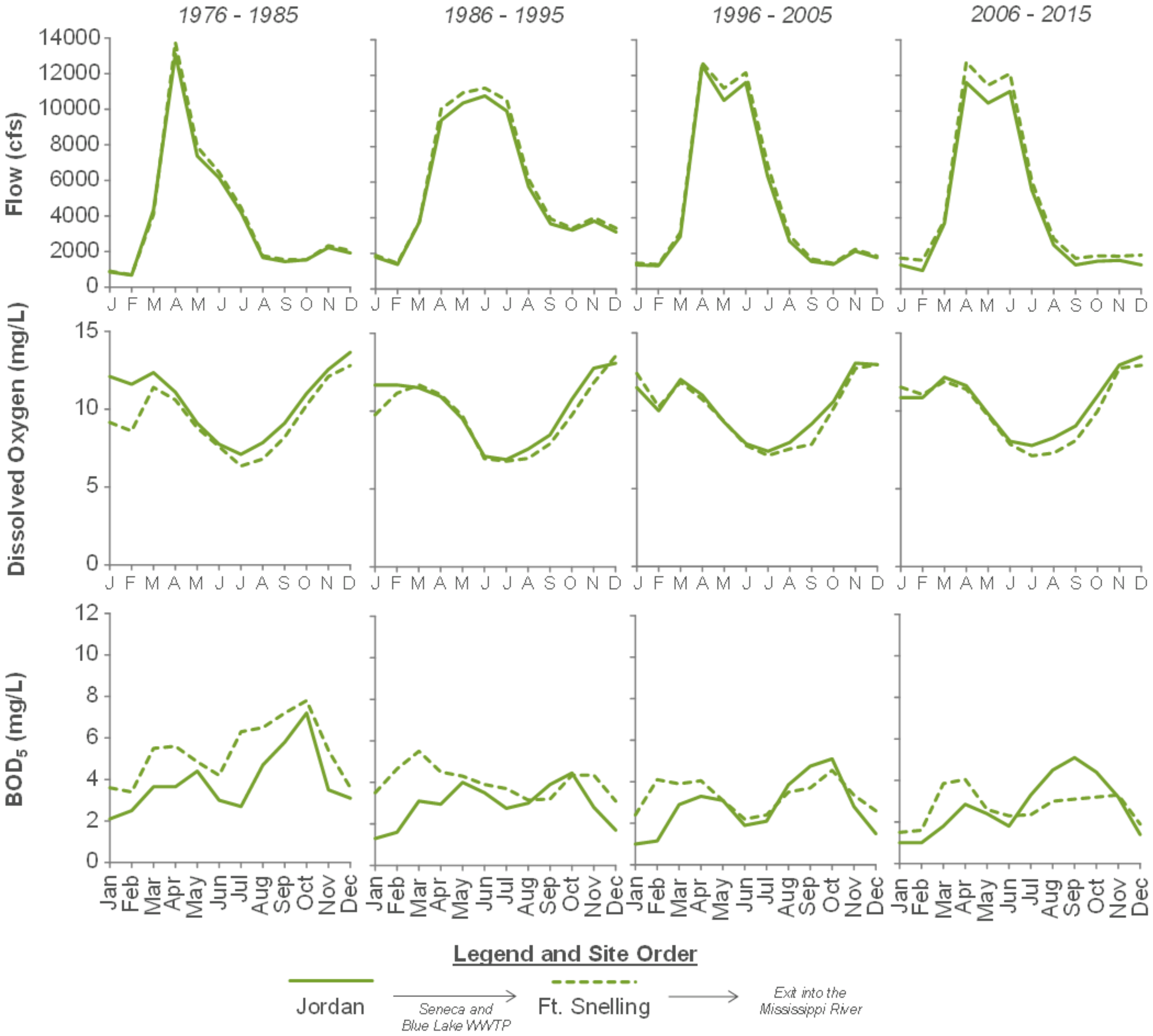


Figure 41. Long-Term Trends of Minnesota River Flow-Adjusted Concentrations of BOD_5, 1976-2015

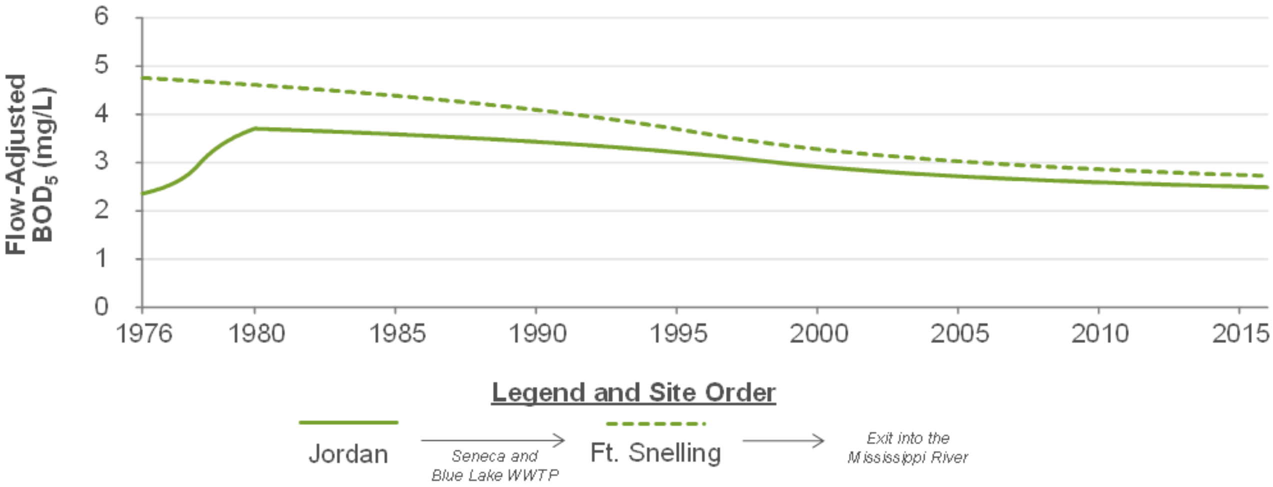


Table 13. Water Quality Trends of Minnesota River Flow-Adjusted Concentrations of BOD_5, 1976-2015

Site	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End
Jordan	6	2.4	2.5
Fort Snelling	-43	4.8	2.7

Temperature, pH, and Conductivity

Minnesota River annual patterns for temperature, pH, and conductivity are presented in Figure 42, and monthly patterns by decade are presented in Figure 43.

Figure 42. Annual Patterns of Minnesota River Median Flows, Temperature, pH, and Conductivity, 1976-2015

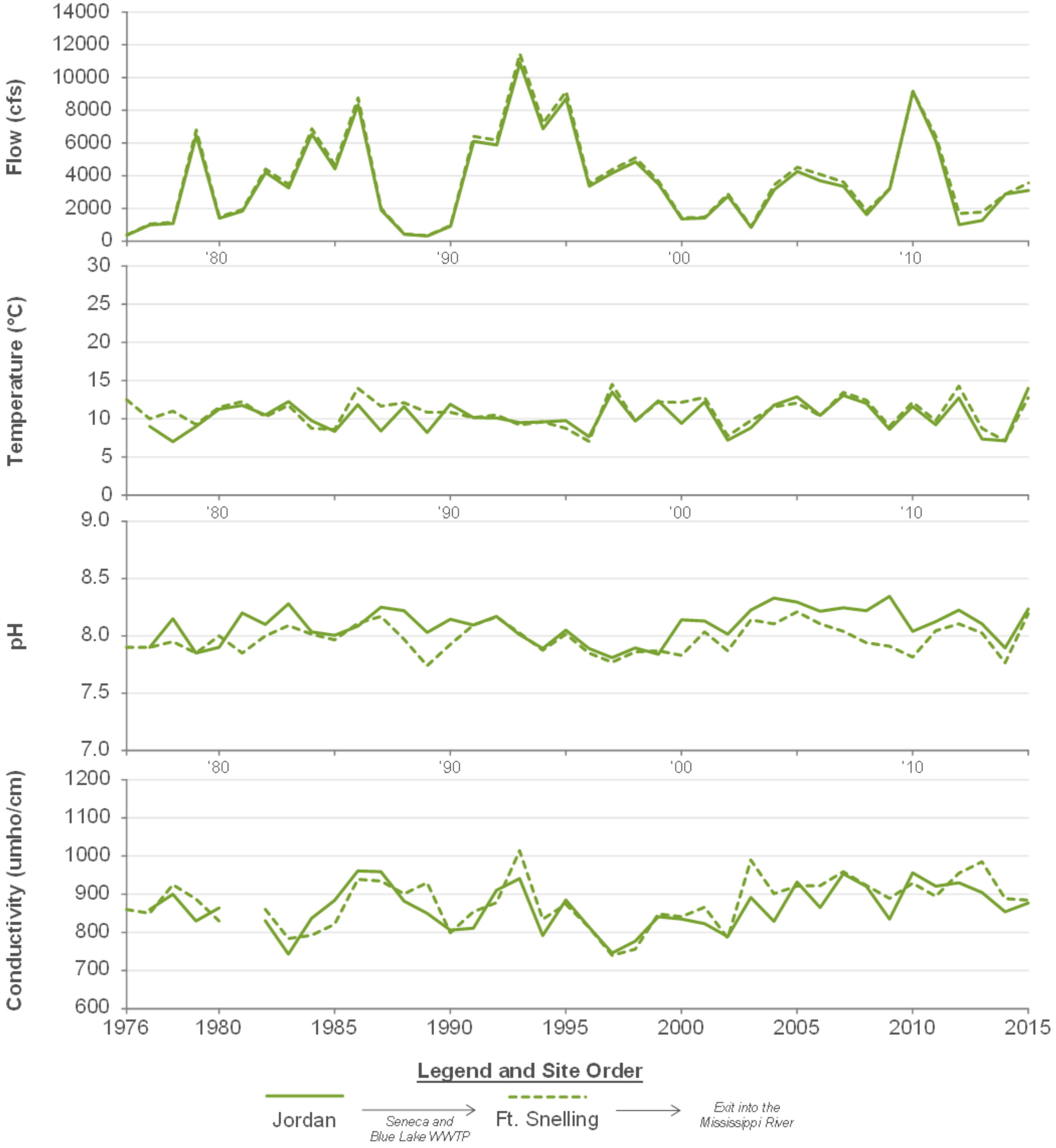
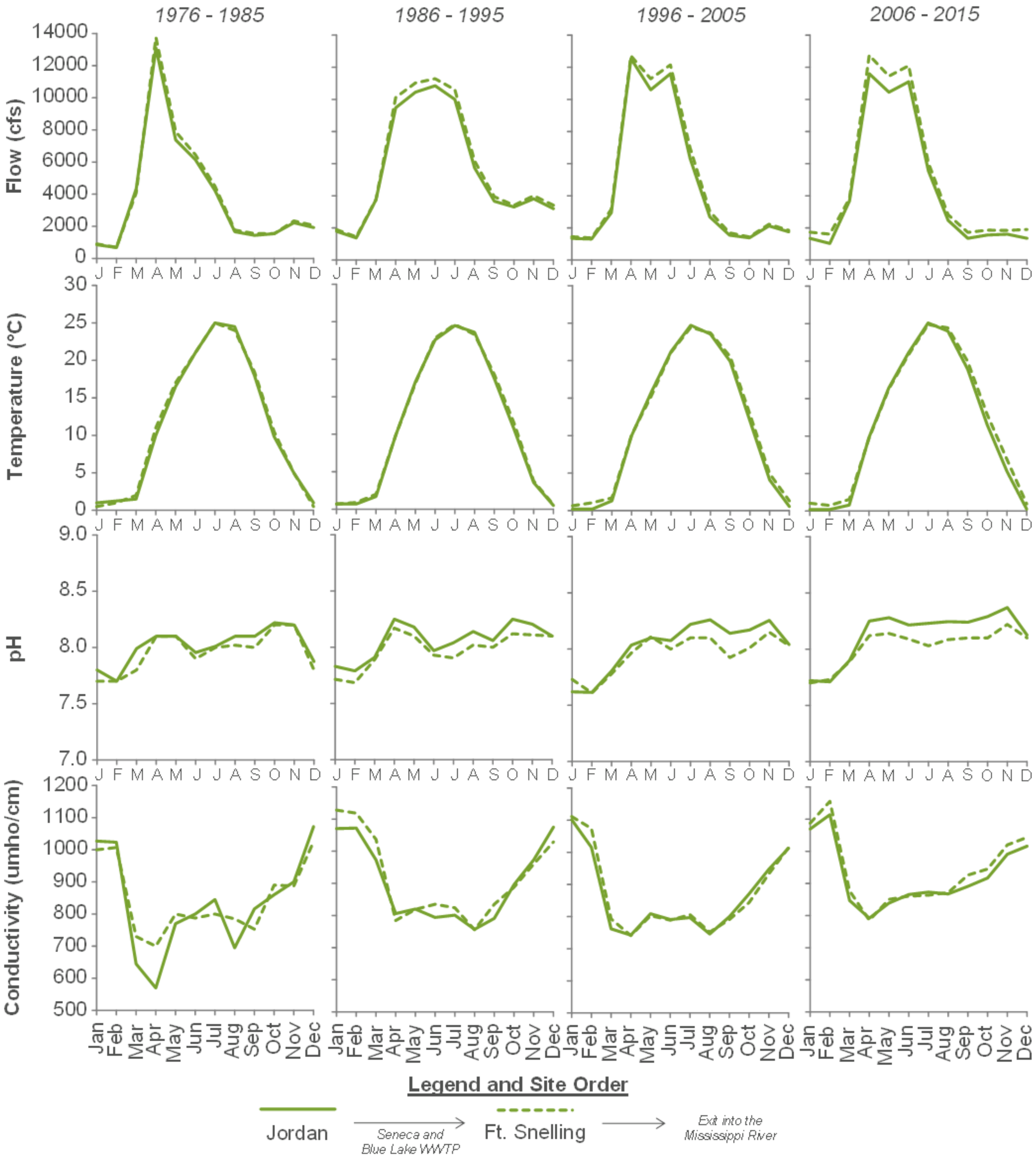


Figure 43. Monthly Patterns of Minnesota River Median Flows, Temperature, pH, and Conductivity by Decade, 1976-2015



Total Suspended Solids (TSS), Total Phosphorus (TP), and Corrected Chlorophyll-*a* (Chl-*a*)

Minnesota River annual patterns for TSS, TP, and Chl-*a* are presented in Figure 44, and the monthly patterns by decade are presented in Figure 45. Minnesota River QWTREND results for TSS, TP, and Chl-*a* are presented in Figure 46. Table 14 lists Minnesota River water quality trends for these three parameters, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 44. Annual Patterns of Minnesota River Median Flows and Concentrations of Total Suspend Solids, Total Phosphorus, and Corrected Chlorophyll-*a*, 1976-2015

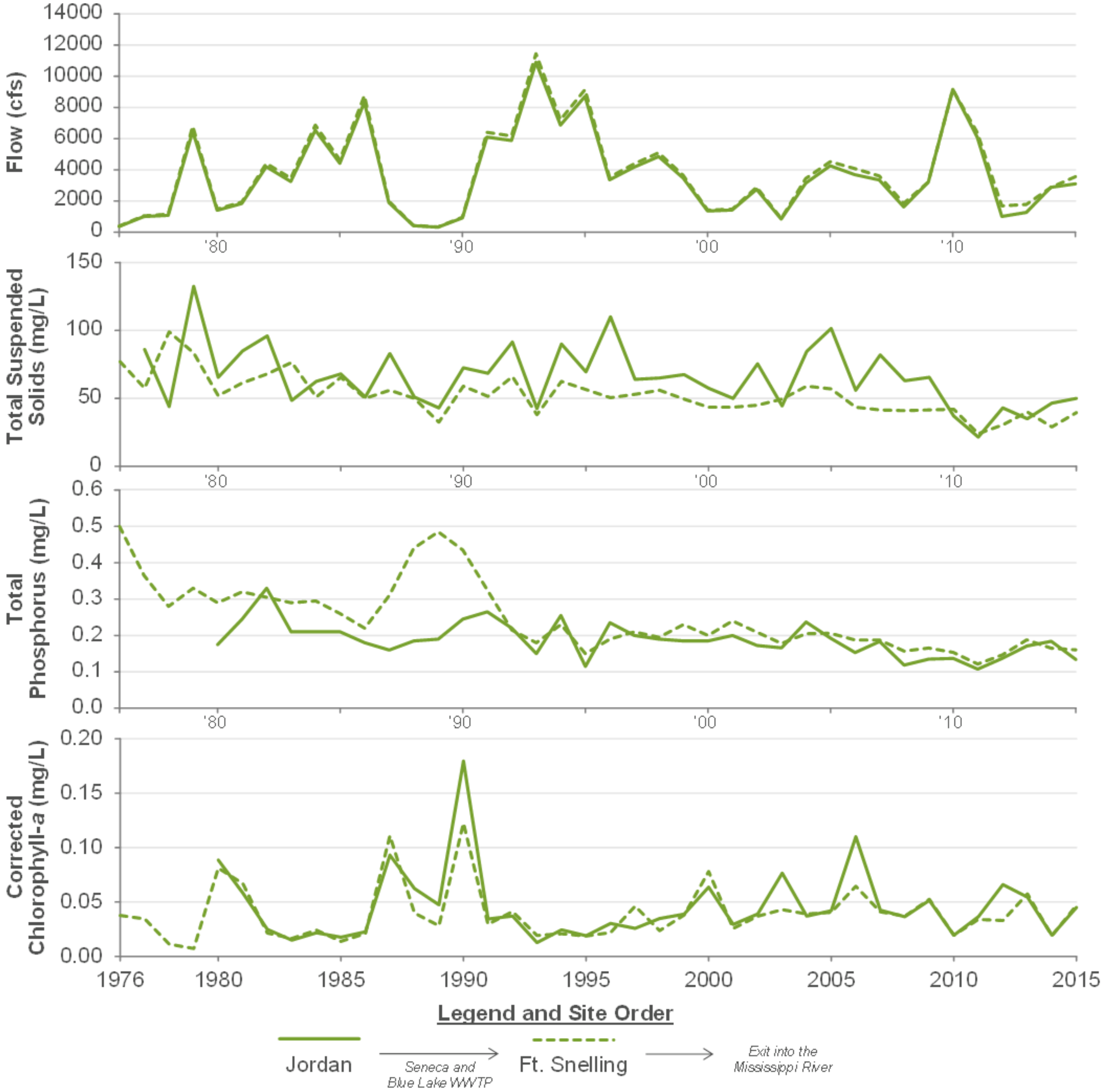


Figure 45. Monthly Patterns of Minnesota River Median Flows and Concentrations of Total Suspend Solids, Total Phosphorus, and Corrected Chlorophyll-*a* by Decade, 1976-2015

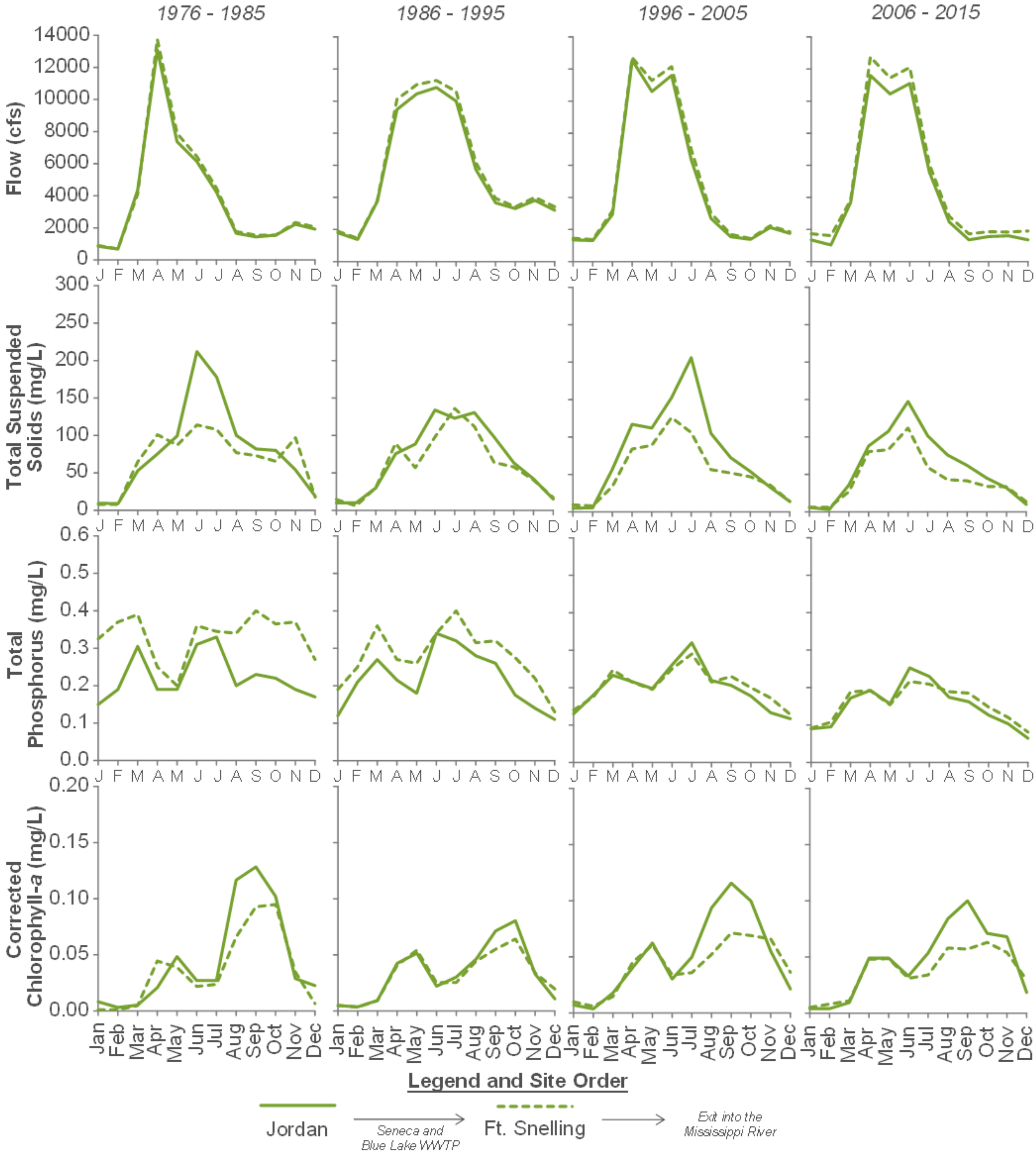


Figure 46. Long-Term Trends of Minnesota River Flow-Adjusted Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a*, 1976-2015

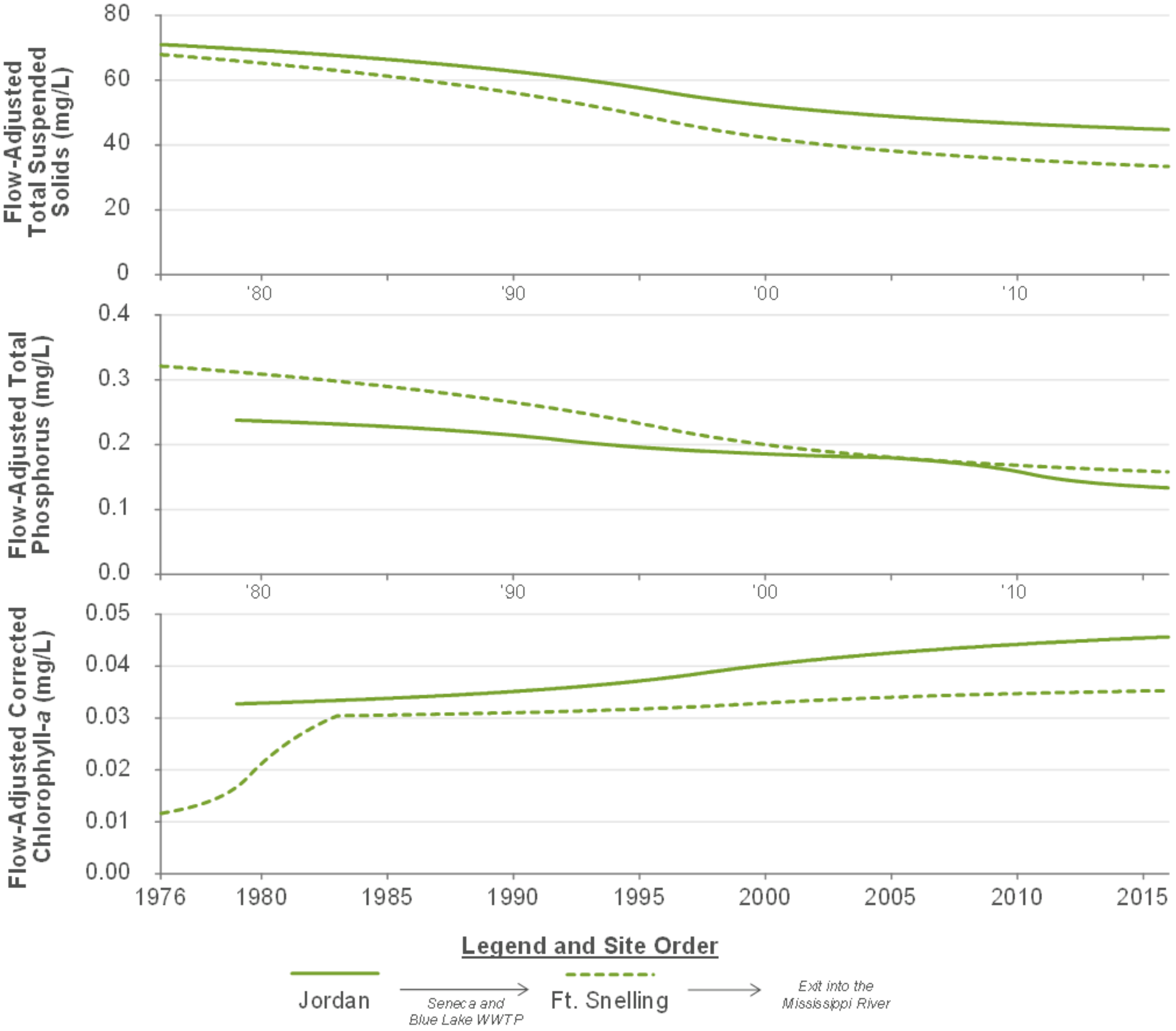


Table 14. Water Quality Trends of Minnesota River Flow-Adjusted Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a*, 1976-2015*

Site	TSS			TP			Chl-*a*		
	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)		Overall Trend (%)	Flow-Adjusted Conc. (mg/L)		Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End		Start	End		Start	End
Jordan	-37	71.0	44.8	-44	0.24	0.13	39	0.033	0.046
Fort Snelling	-51	67.9	33.4	-51	0.32	0.16	PT	-	-

* Assessment Period at Jordan: 1976 to 2015 for TSS, 1979 to 2015 for TP and Chl-*a*

PT - Partial Trend: One of the sub-trends within the trend model was not statistically significant, so a representative overall percentage change could not be calculated.

Total Nitrogen (TN), Nitrate-Nitrogen (NO_3), and Ammonia-Nitrogen (NH_3)

Minnesota River annual patterns for TN, NO_3, NH_3, are presented in Figure 47, and monthly patterns by decade are presented in Figure 48. Minnesota River QWTREND results for TN, NO_3, and NH_3 are presented in Figure 49. Table 15 lists Minnesota River water quality trends for TN, NO_3, and NH_3, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 47. Annual Patterns of Minnesota River Median Flows and Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen, 1976-2015

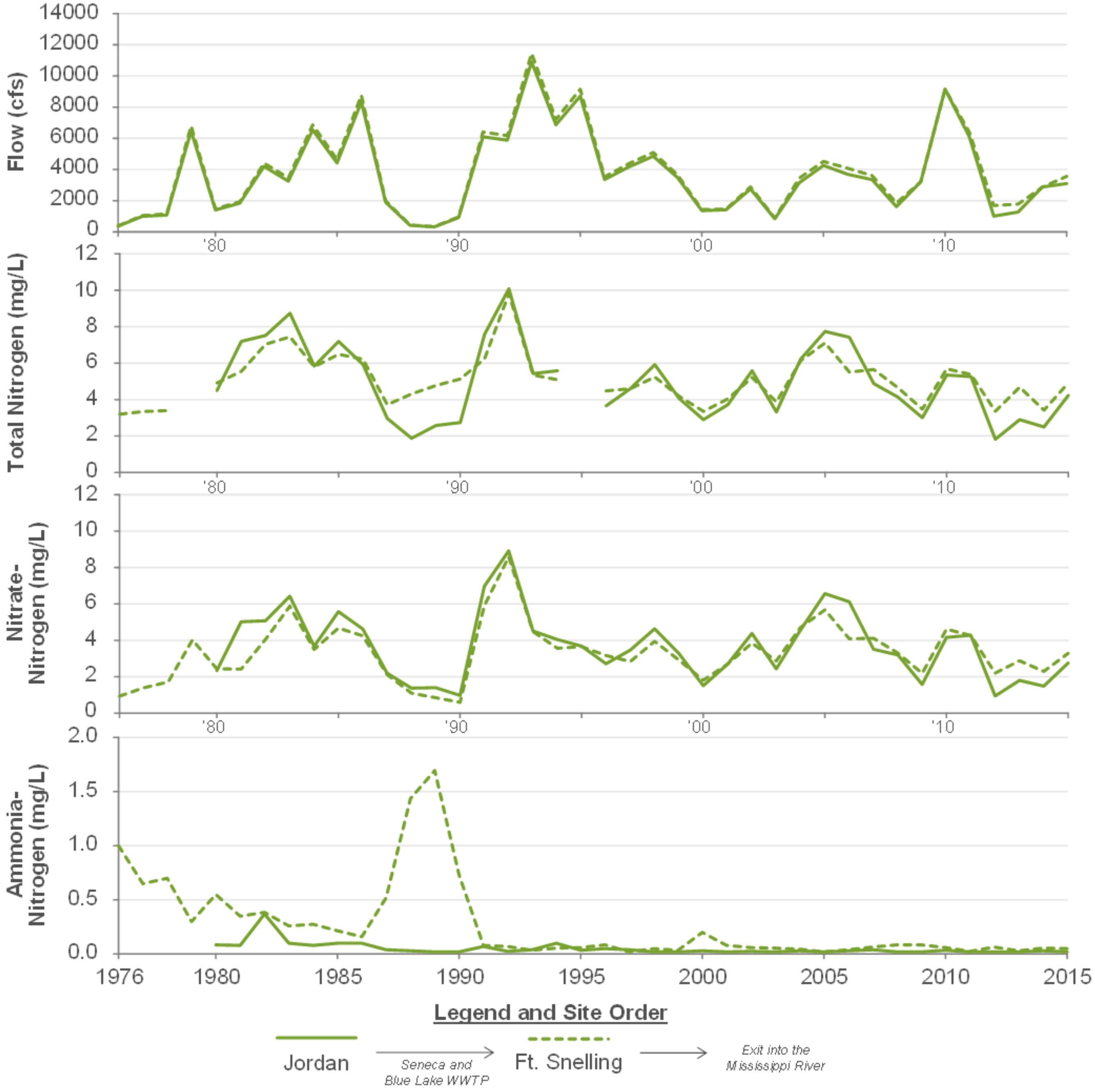


Figure 48. Monthly Patterns of Minnesota River Median Flows and Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen by Decade, 1976-2015

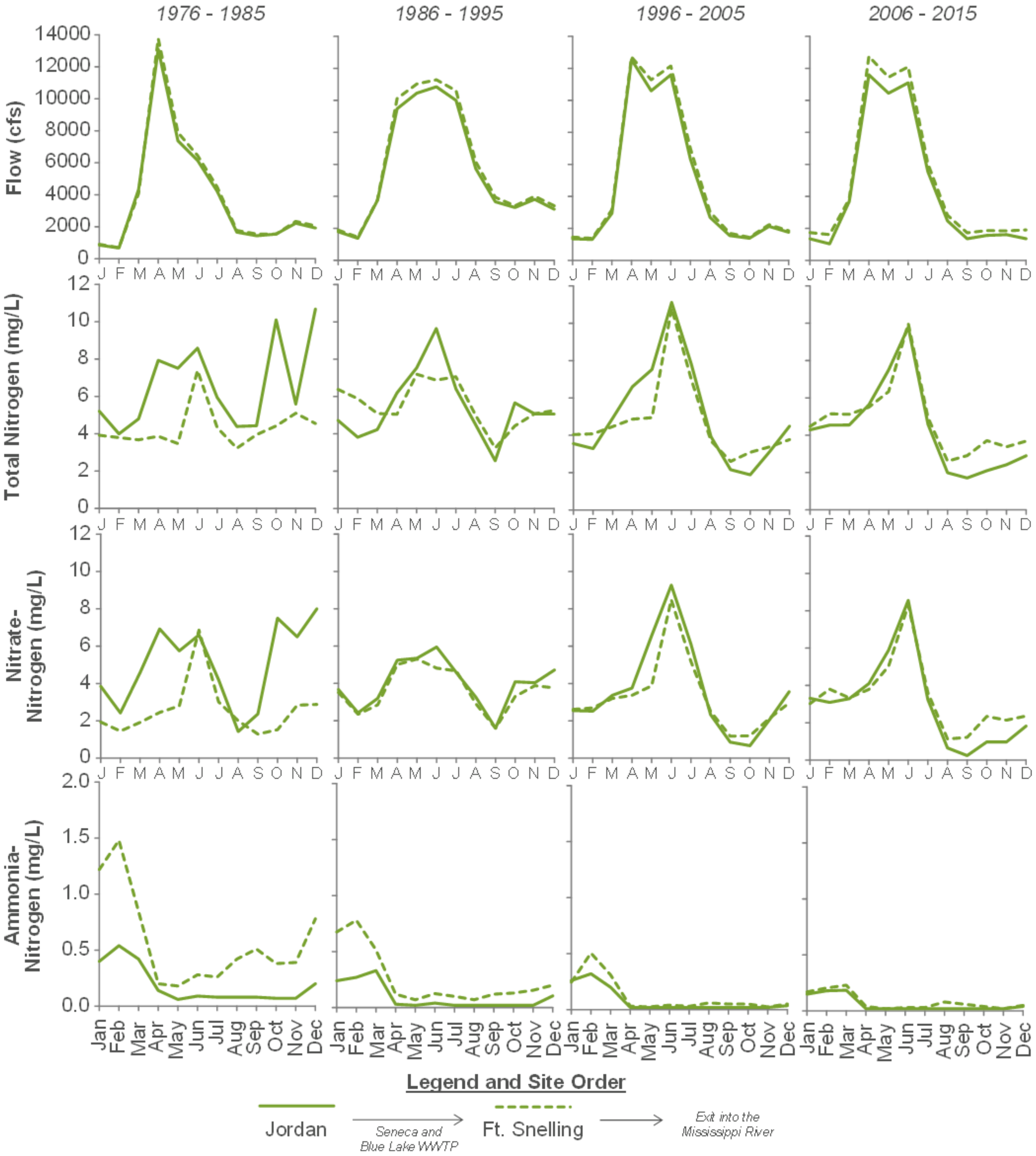


Figure 49. Long-Term Trends of Minnesota River Flow-Adjusted Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen, 1976-2015

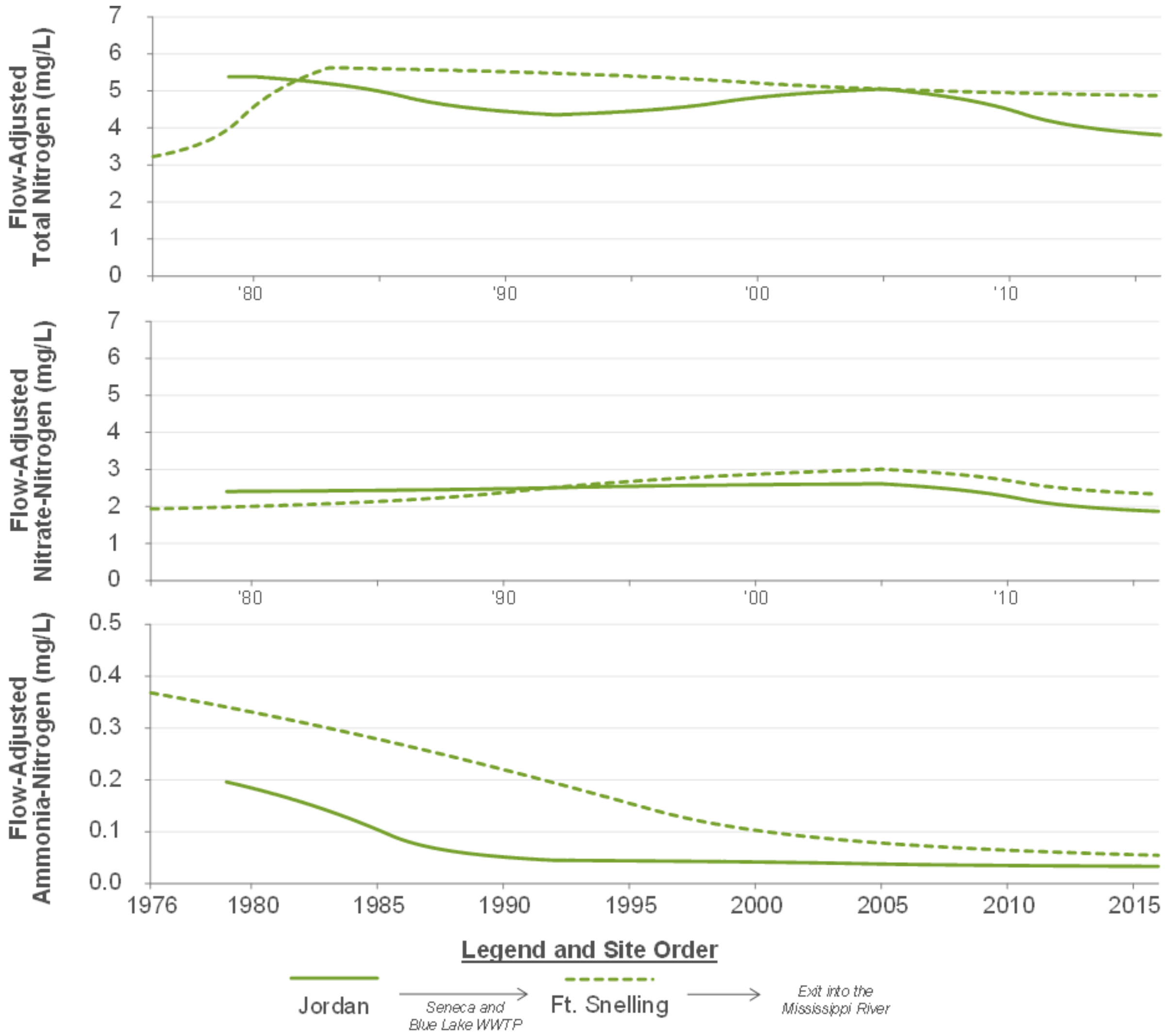


Table 15. Water Quality Trends of Minnesota River Flow-Adjusted Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen, 1976 to 2015*

Site	TN			NO_3			NH_3		
	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)		Overall Trend (%)	Flow-Adjusted Conc. (mg/L)		Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End		Start	End		Start	End
Jordan	-29	5.4	3.8	PT	-	-	BRL	-	-
Fort Snelling	51	3.2	4.9	21	1.9	2.3	BRL	-	-

* Assessment Period at Jordan: 1979 to 2015 for NO_3 and 1980 to 2015 for TN

PT - Partial Trend: One of the sub-trends within the trend model was not statistically significant, so a representative overall percentage change could not be calculated.

BRL - Below Reporting Limit: More than 10% of the data were below than the lab's RL, so a representative overall percentage change could not be calculated.

Fecal Coliform (FC) and *Escherichia coli* (*E. coli*) Bacteria

Minnesota River annual patterns for FC and *E. coli* are presented in Figure 50, and monthly patterns by decade are presented in Figure 51. Minnesota River QWTREND results for FC are presented in Figure 52. Table 16 lists Minnesota River water quality trends for FC, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 50. Annual Patterns of Minnesota River Median Flows and Concentrations of Fecal Coliform and *E. coli*, 1976-2015

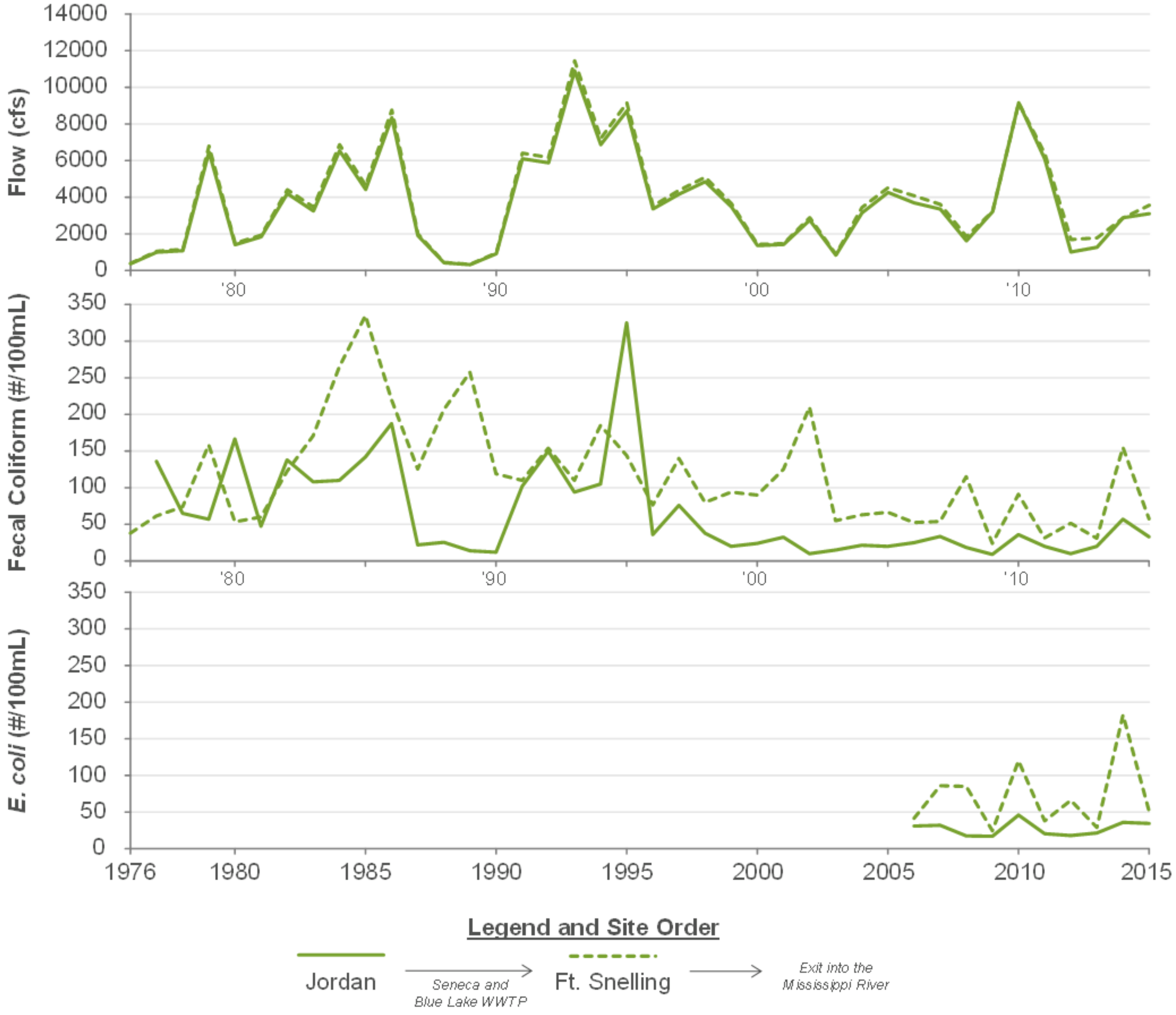


Figure 51. Monthly Patterns of Minnesota River Median Flows and Concentrations of Fecal Coliform and *E. coli* by Decade, 1976-2015

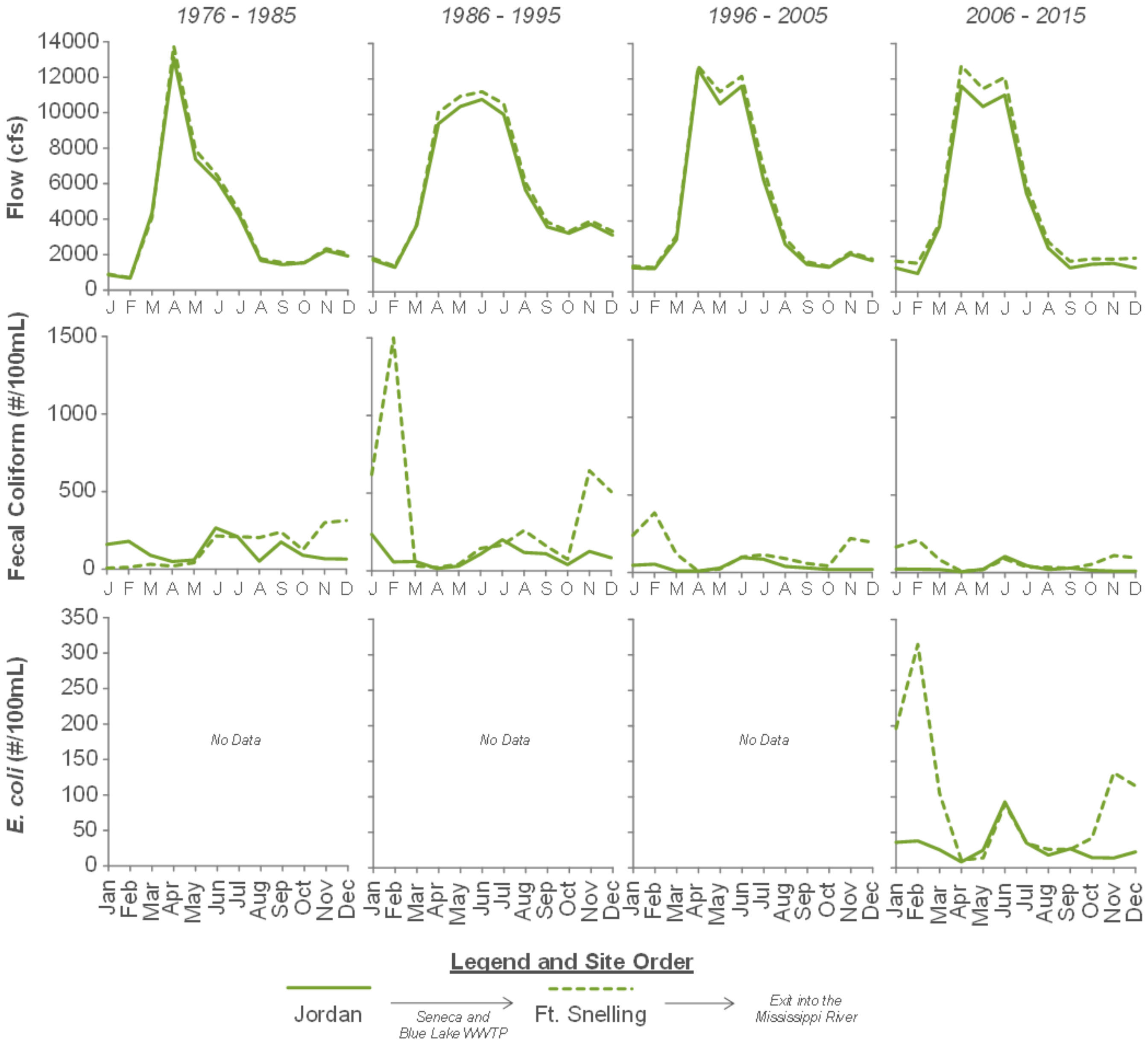


Figure 52. Long-Term Trends of Minnesota River Flow-Adjusted Concentrations of Fecal Coliform, 1976-2015

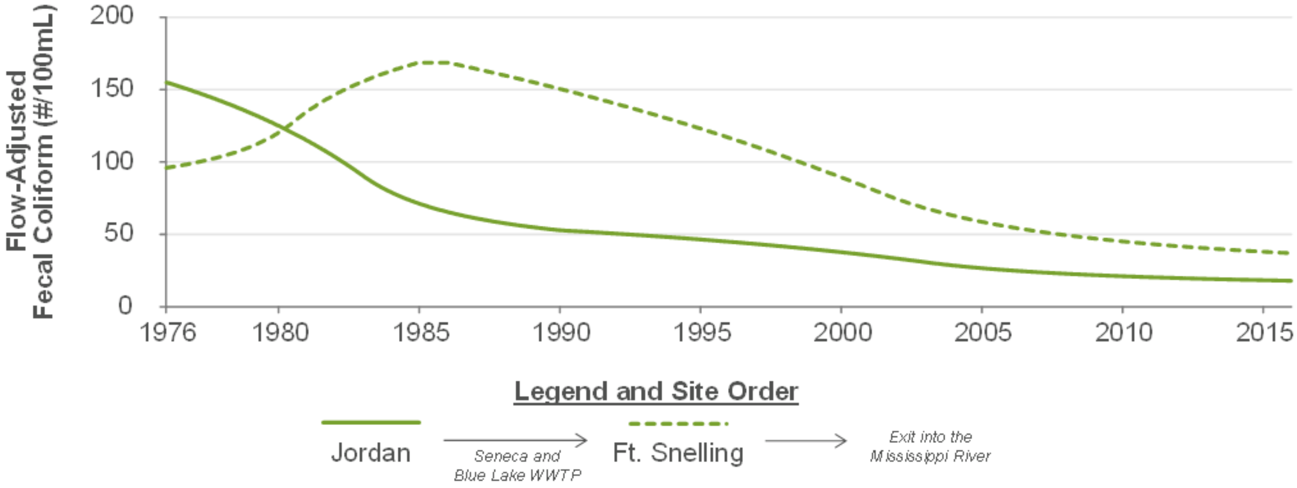


Table 16. Water Quality Trends of Minnesota River Flow-Adjusted Concentrations of Fecal Coliform, 1976-2015

Site	**Overall Trend (%)**	**Flow-Adjusted Conc. (mg/L)**	
		Start	**End**
Jordan	-88	155	18
Fort Snelling	-61	96	37

Chloride (Cl)

Minnesota River annual patterns for Cl are presented in Figure 53, and monthly patterns by decade are presented in Figure 54. Minnesota River QWTREND results for Cl are presented in Figure 55. Table 17 lists Minnesota River water quality trends for Cl, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 53. Annual Patterns of Minnesota River Median Flows and Concentrations of Chloride, 1985-2015

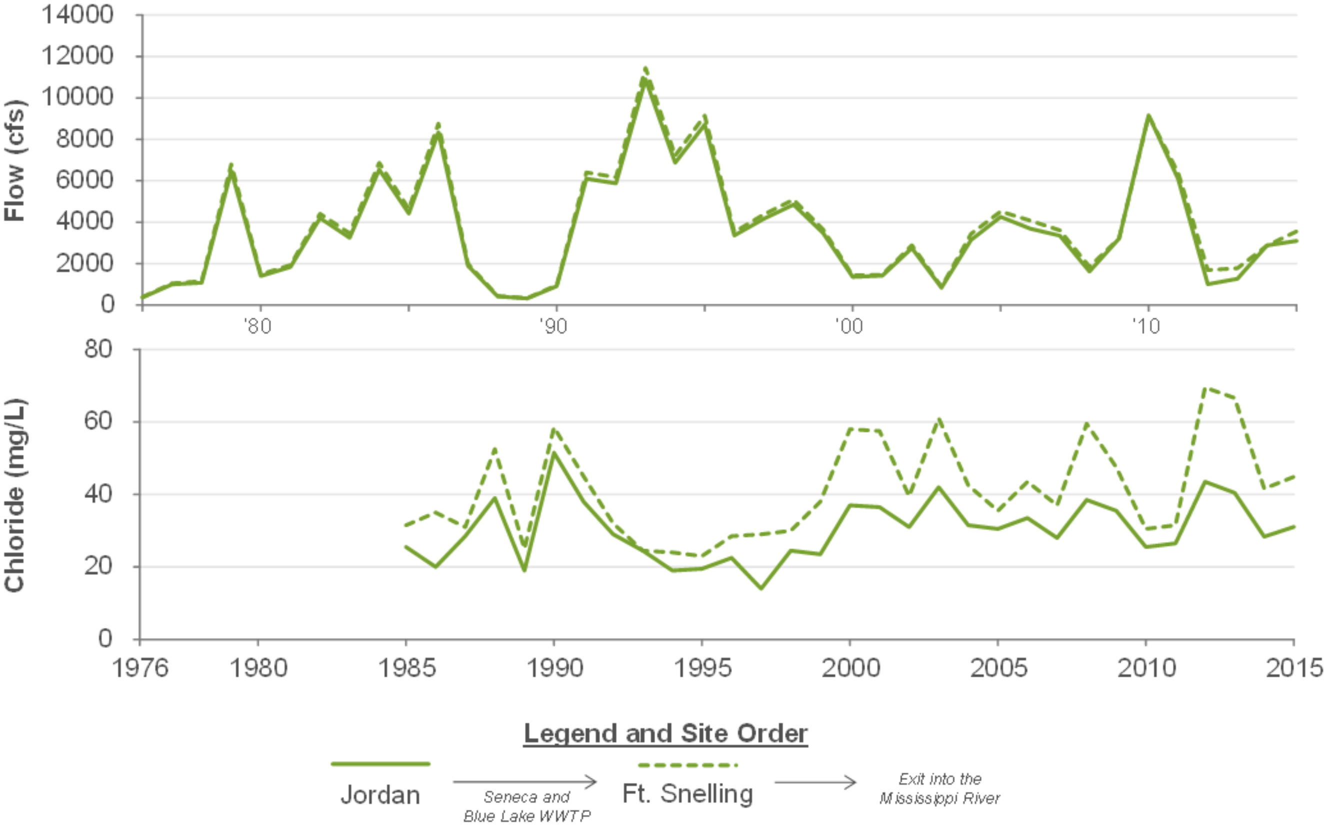


Figure 54. Monthly Patterns of Minnesota River Median Flows and Concentrations of Chloride by Decade, 1985-2015

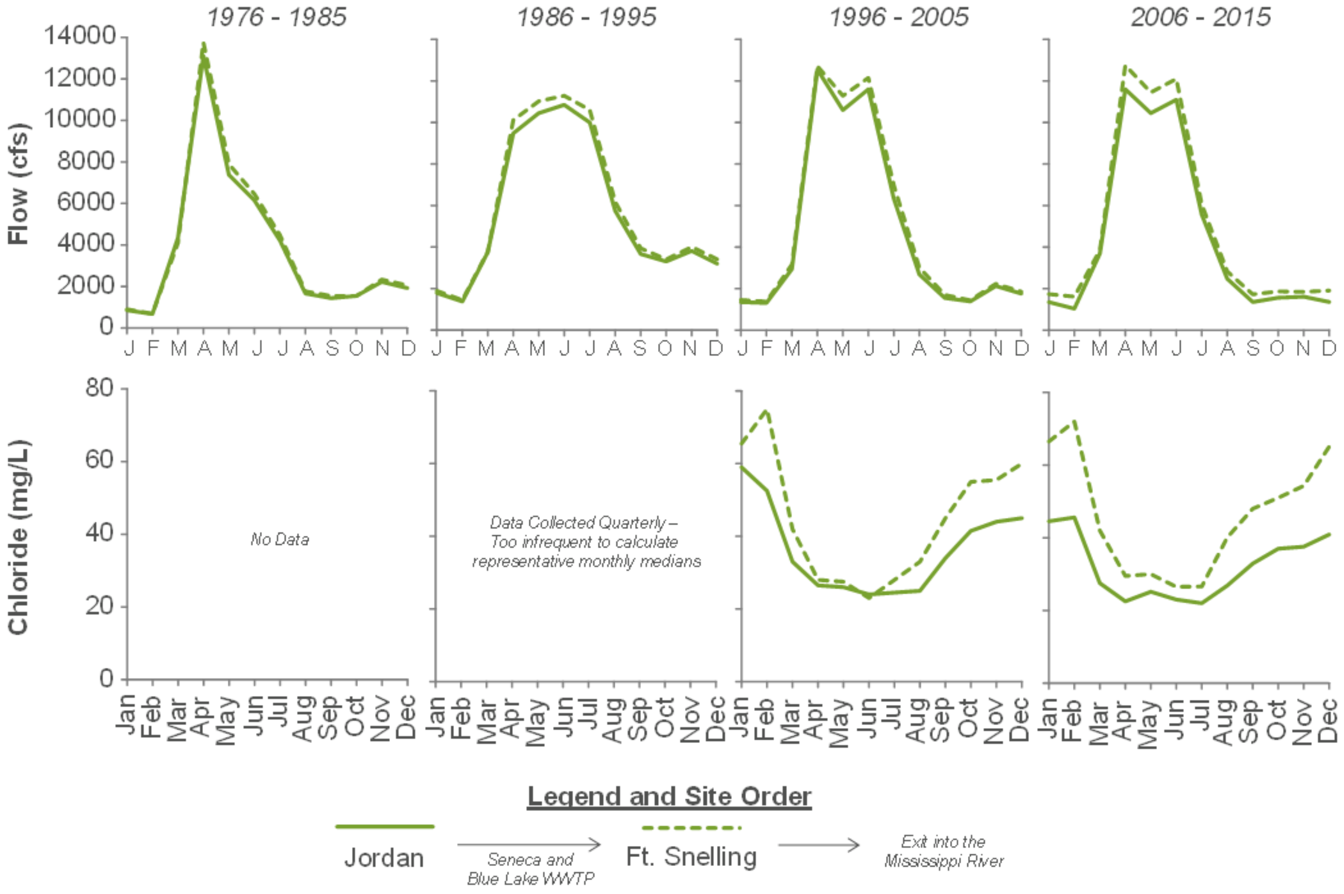


Figure 55. Long-Term Trends of Minnesota River Water Flow-Adjusted Concentrations of Chloride, 1985-2015

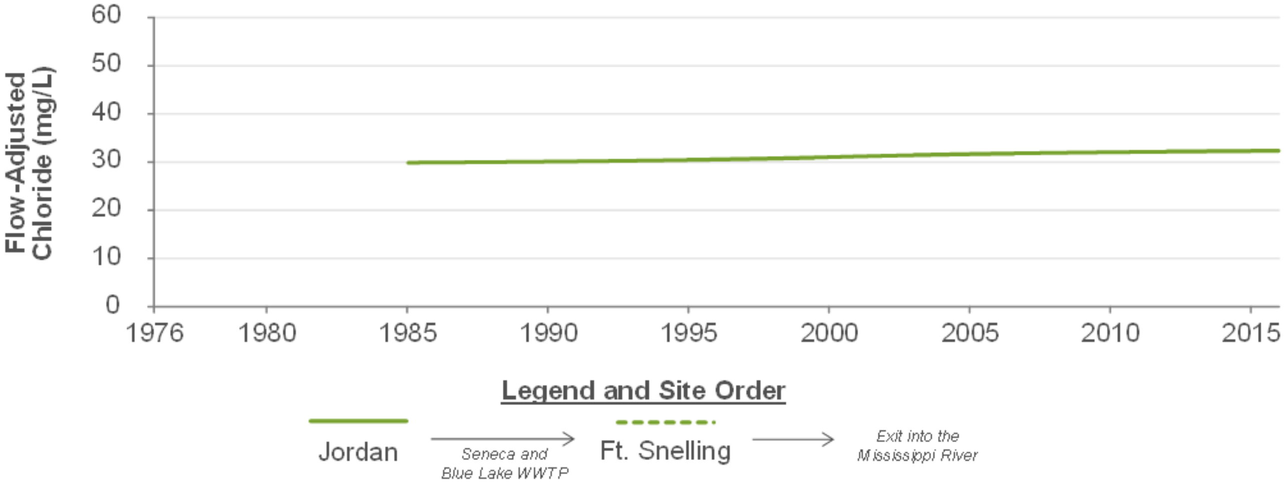


Table 17. Water Quality Trends of Minnesota River Flow-Adjusted Concentrations of Chloride, 1985-2015

Site	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End
Jordan	8	29.8	32.4
Fort Snelling	NT	-	-

NT – No Trend: A statistically significant trend model did not fit the data. Refer to the “Appendix” for more information on the non-significant Fort Snelling trend.

St. Croix River

Precipitation and Flow

Total annual precipitation at the MSP airport and the St. Croix River annual patterns of median flow and flow volume are presented in Figure 56. Monthly patterns by decade for total precipitation at the MSP airport and for the St. Croix River median flow are presented in Figure 57.

Figure 56. Annual Patterns of Precipitation (MSP Airport) and Median St. Croix River Flows and Flow Volumes, 1976-2015

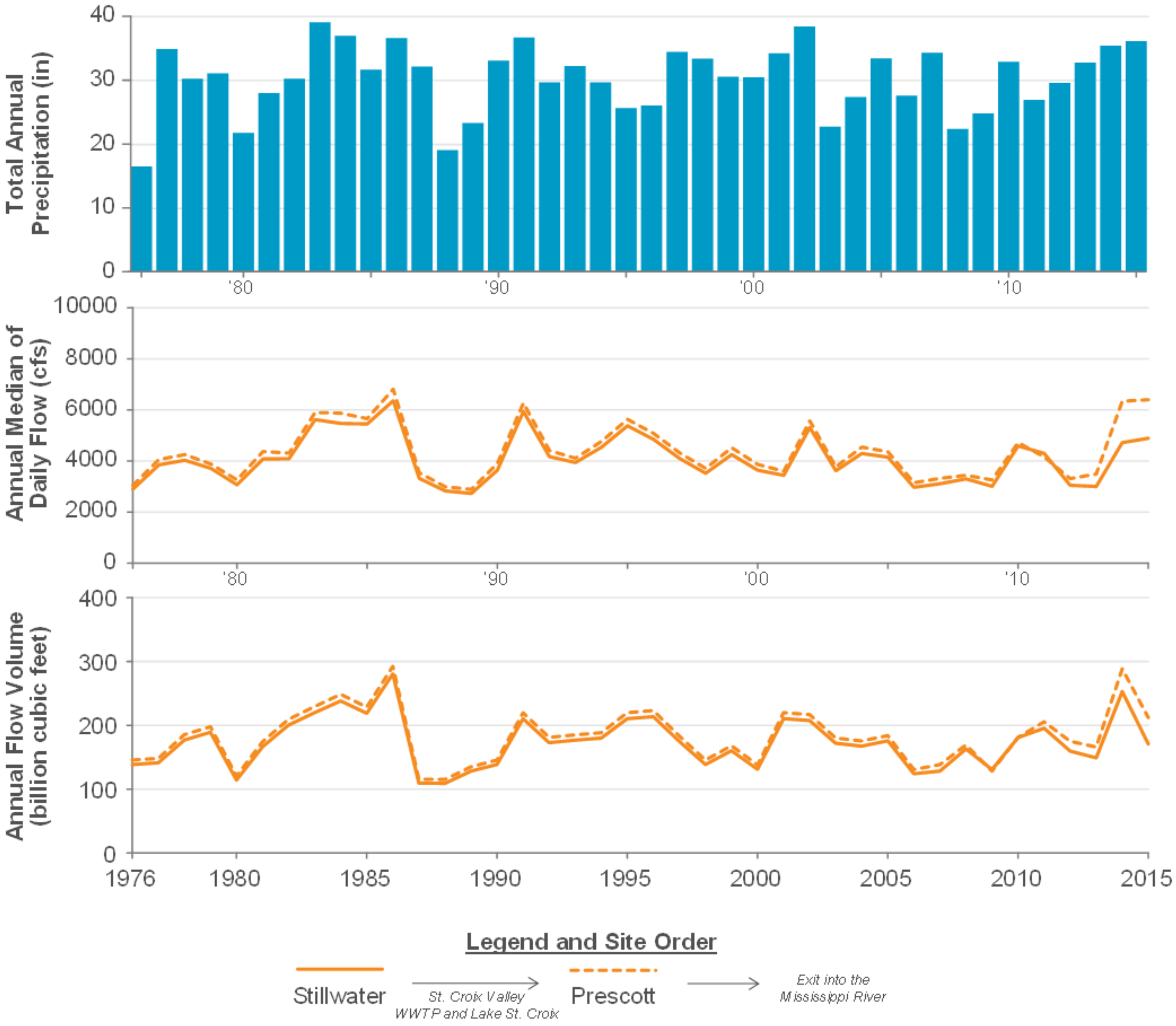
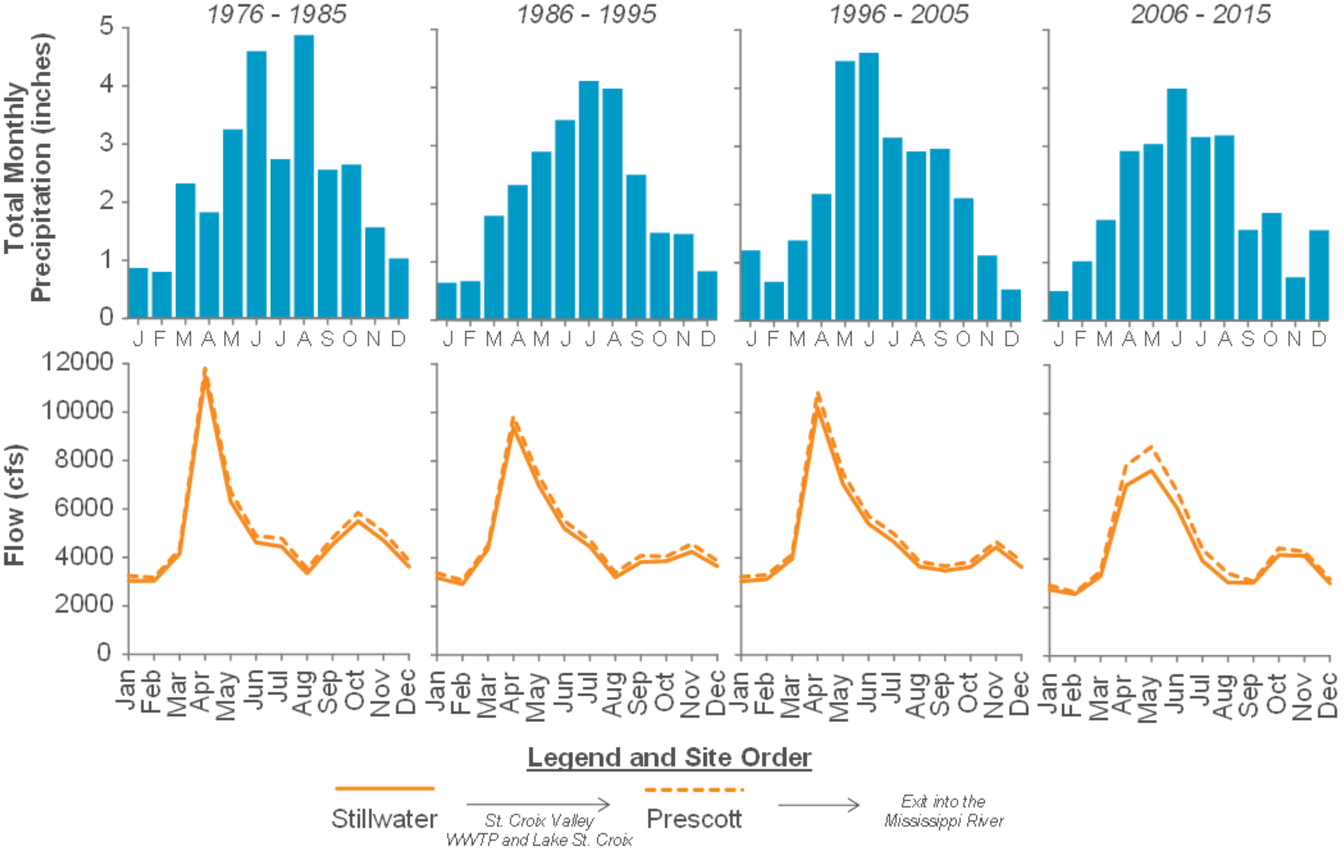


Figure 57. Monthly Patterns of Precipitation (MSP Airport) and Median St. Croix River Flows by Decade, 1976-2015



Dissolved Oxygen (DO) and 5-Day Biochemical Oxygen Demand (BOD_5)

St. Croix River annual patterns for DO and BOD_5 are presented in Figure 58, and monthly patterns by decade are presented in Figure 59. The St. Croix River QWTREND results for BOD_5 are presented in Figure 60. Table 18 lists St. Croix River water quality trends for BOD_5, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 58. Annual Patterns of Median St. Croix River Flows and Concentrations of Dissolved Oxygen and BOD_5, 1976-2015

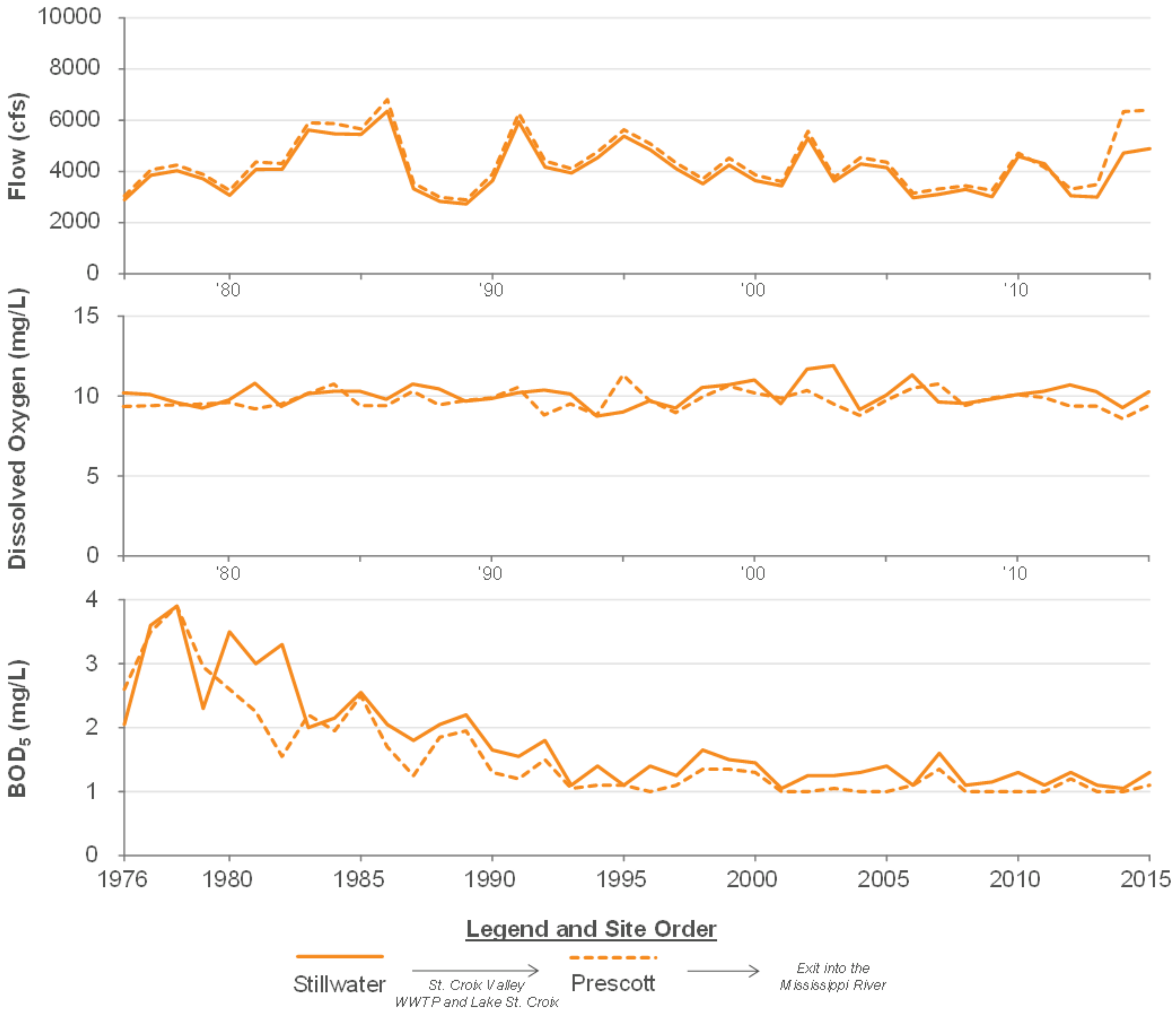


Figure 59. Monthly Patterns of Median St. Croix River Flows and Concentrations of Dissolved Oxygen and BOD$_5$ by Decade, 1976-2015

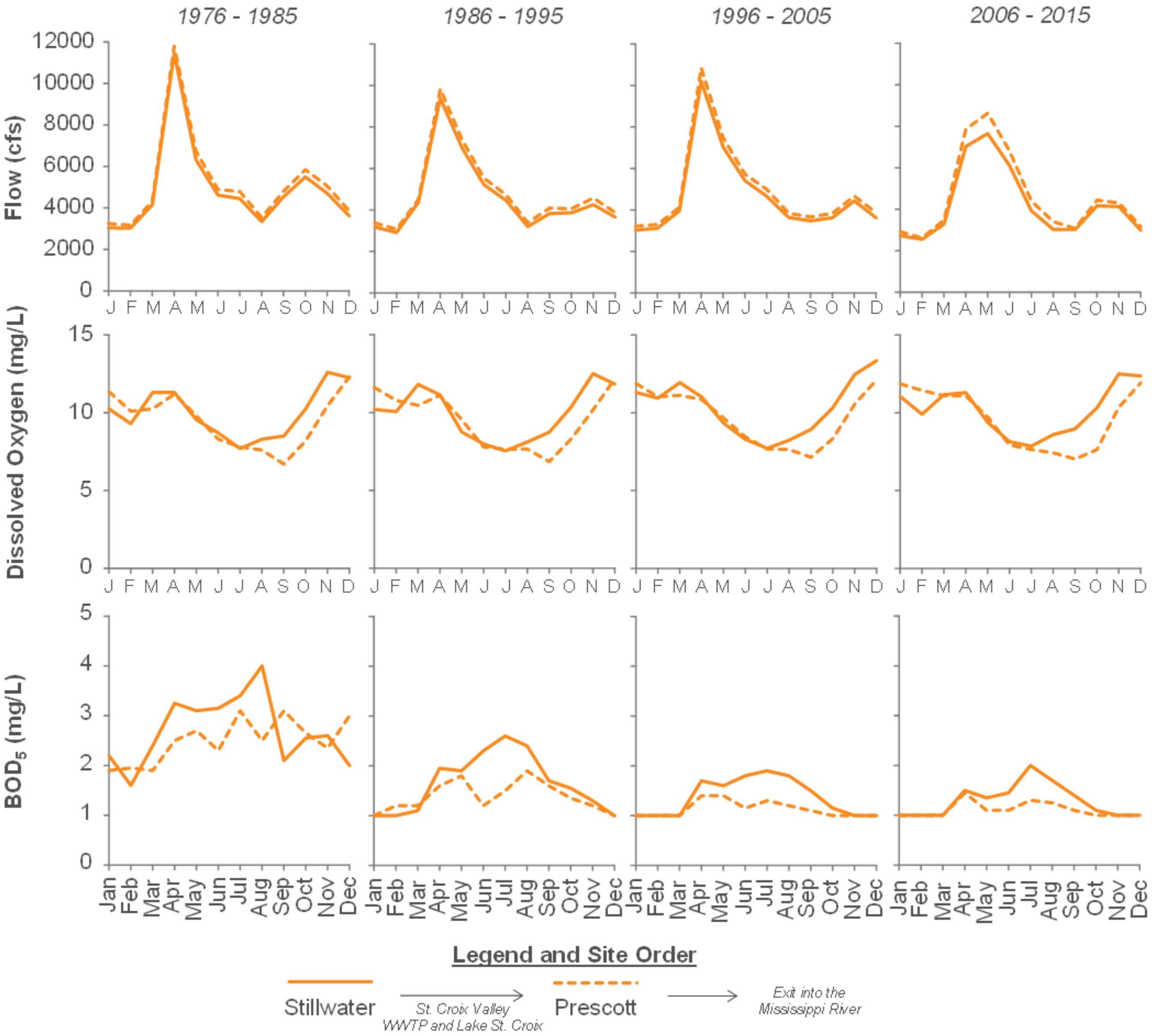


Figure 60. Long-Term Trends of St. Croix River Flow-Adjusted Concentrations of BOD_5, 1976-2015

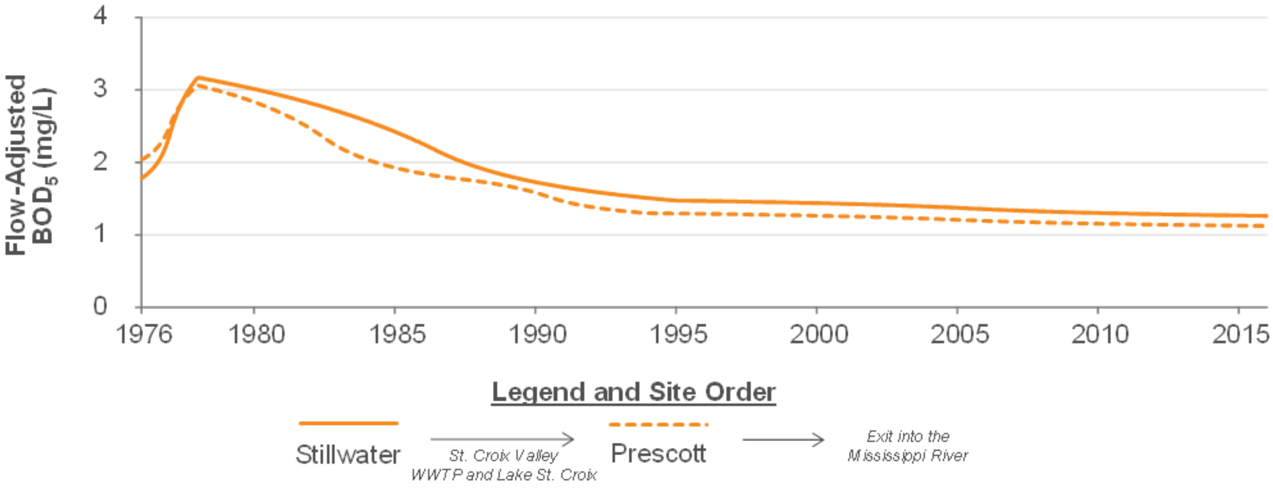


Table 18. Water Quality Trends of St. Croix River Flow-Adjusted Concentrations of BOD_5, 1976-2015

Site	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End
Stillwater	BRL	-	-
Prescott	BRL	-	-

BRL – Below Reporting Limit: More than 10% of the data were below than the lab’s RL, so a representative overall percentage change could not be calculated.

Temperature, pH, and Conductivity

St. Croix River annual patterns for temperature, pH, and conductivity are presented in Figure 61, and monthly patterns by decade are presented in Figure 62.

Figure 61. Annual Patterns of St. Croix River Median Flows, Temperature, pH, and Conductivity, 1976-2015

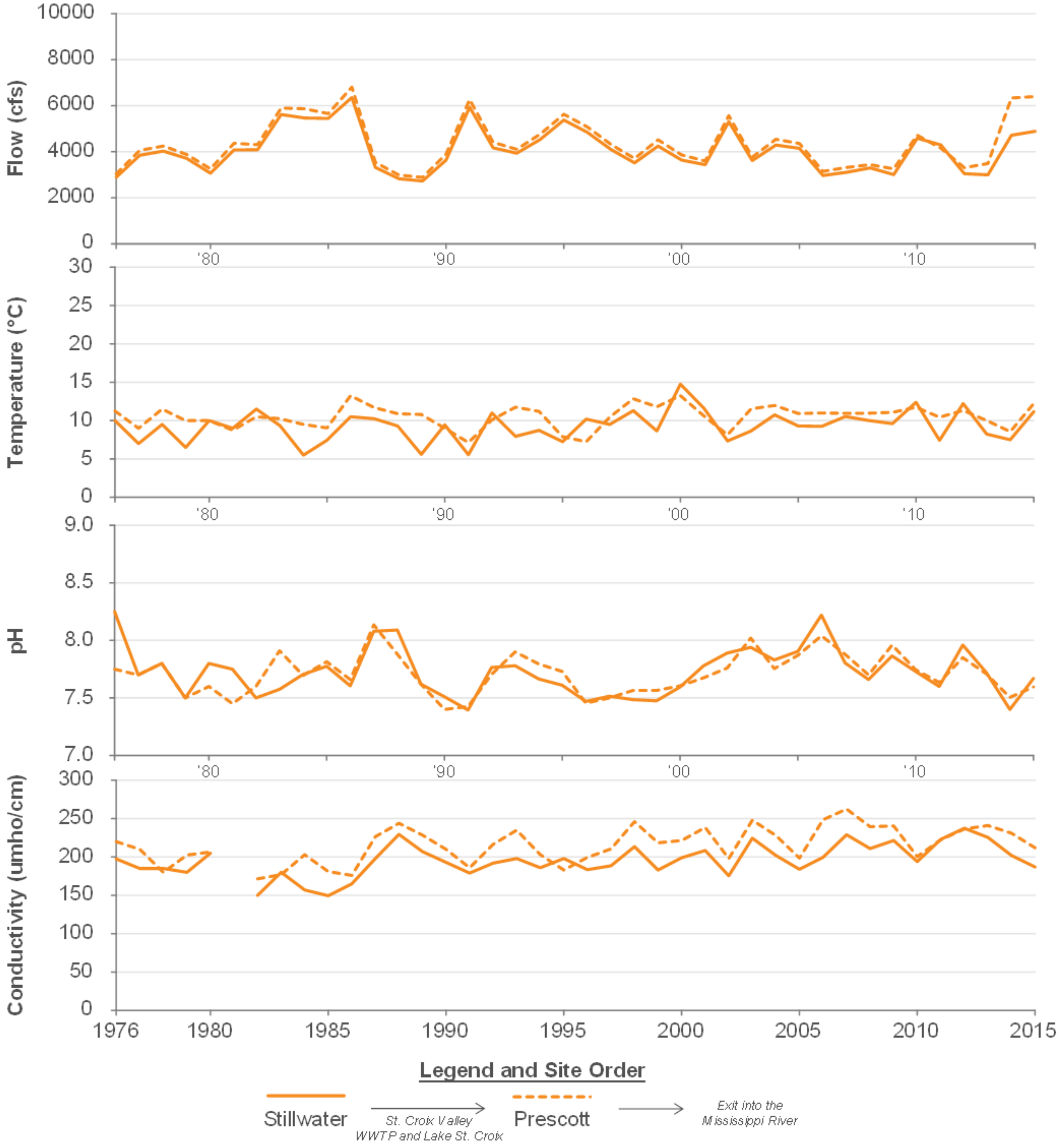
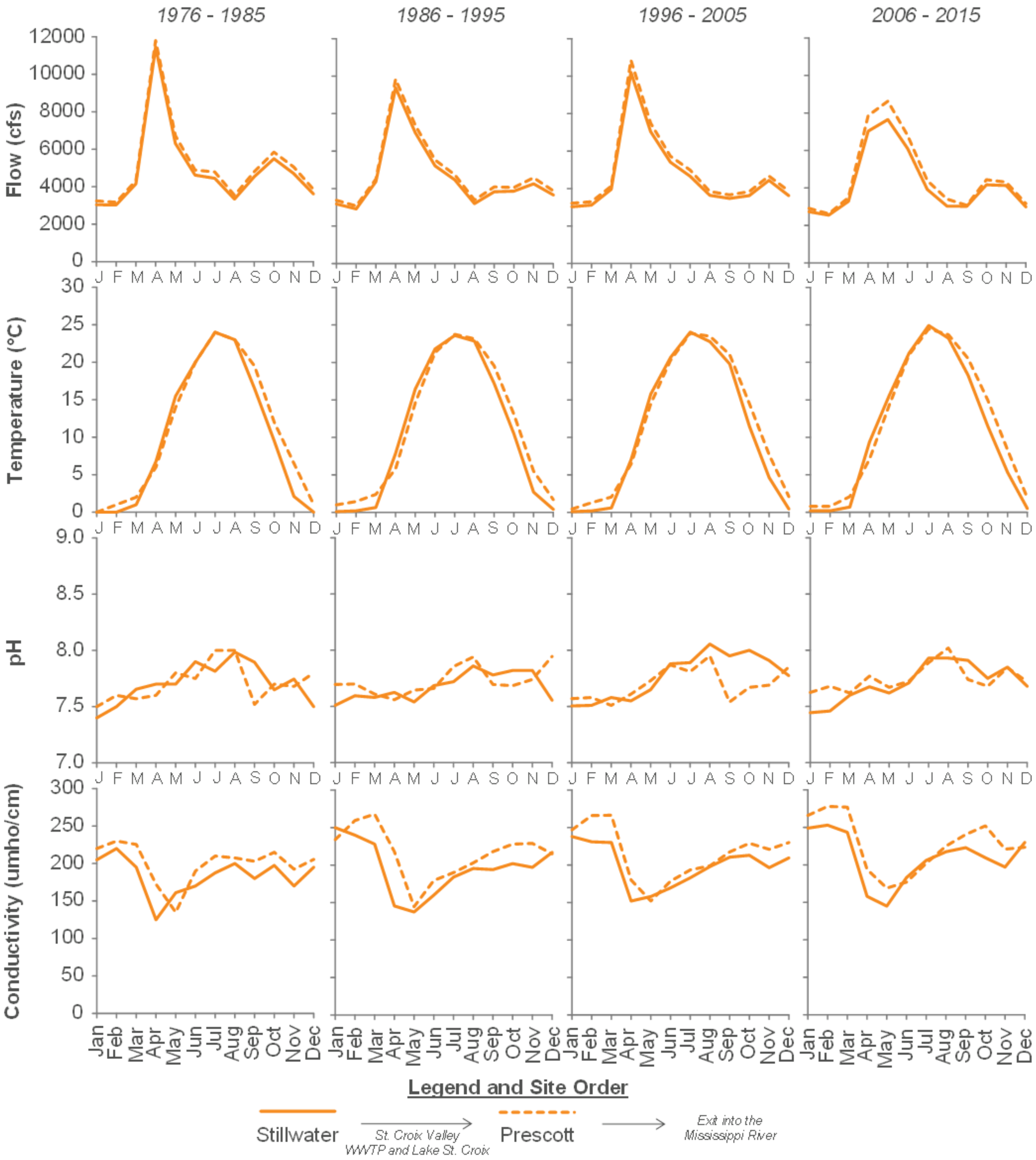


Figure 62. Monthly Patterns of St. Croix River Median Flows, Temperature, pH, and Conductivity by Decade, 1976-2015



Total Suspended Solids (TSS), Total Phosphorus (TP), and Corrected Chlorophyll-*a* (Chl-*a*)

St. Croix River annual patterns for TSS, TP, and Chl-*a* are presented in Figure 63, and monthly patterns by decade are presented in Figure 64. St. Croix River QWTREND results for TSS, TP, and Chl-*a* are presented in Figure 65. Table 19 lists St. Croix River water quality trends for these three parameters, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 63. Annual Patterns of St. Croix River Median Flows and Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a*, 1976-2015

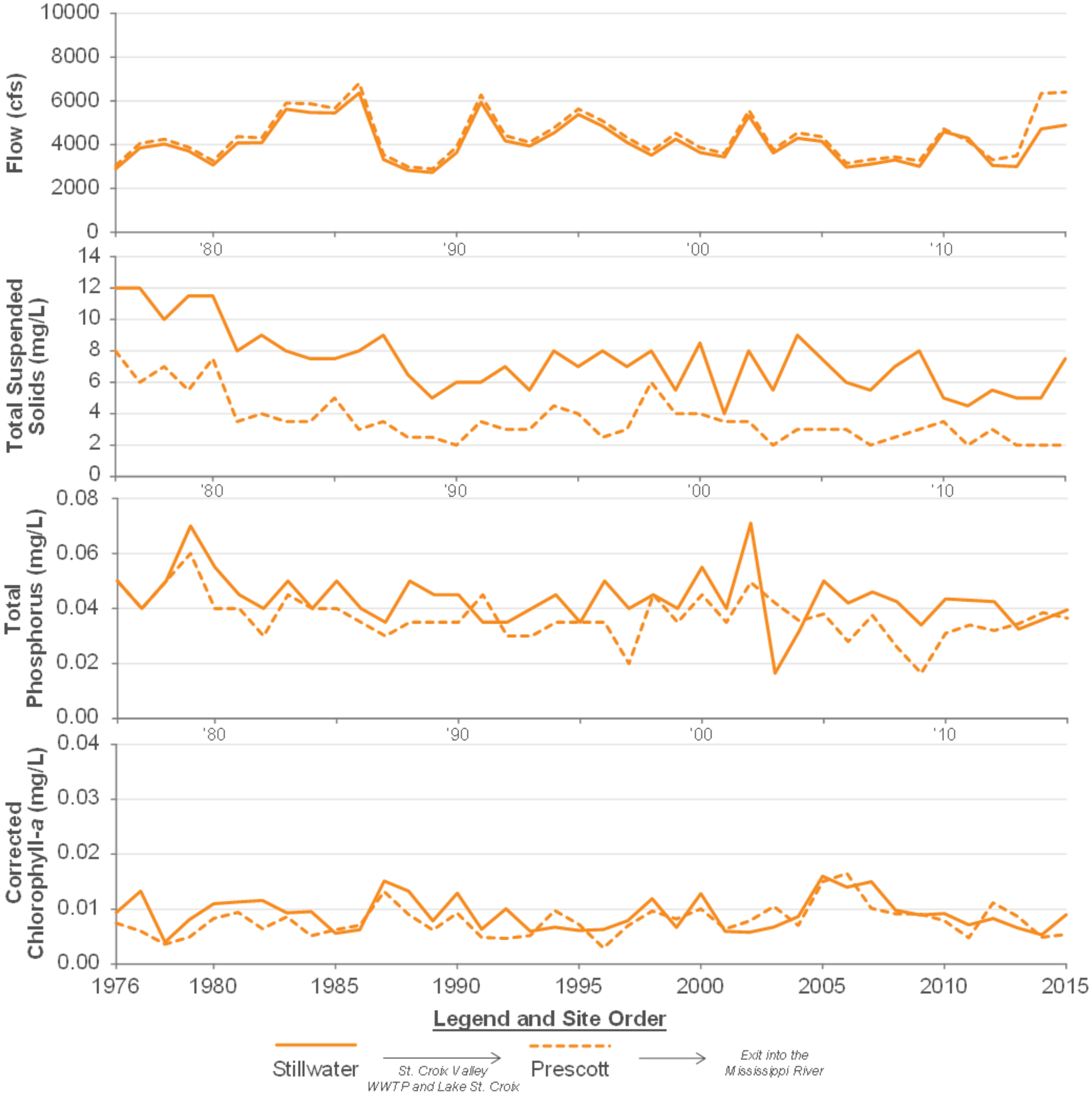


Figure 64. Monthly Patterns of St. Croix River Median Flows and Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a* by Decade, 1976-2015

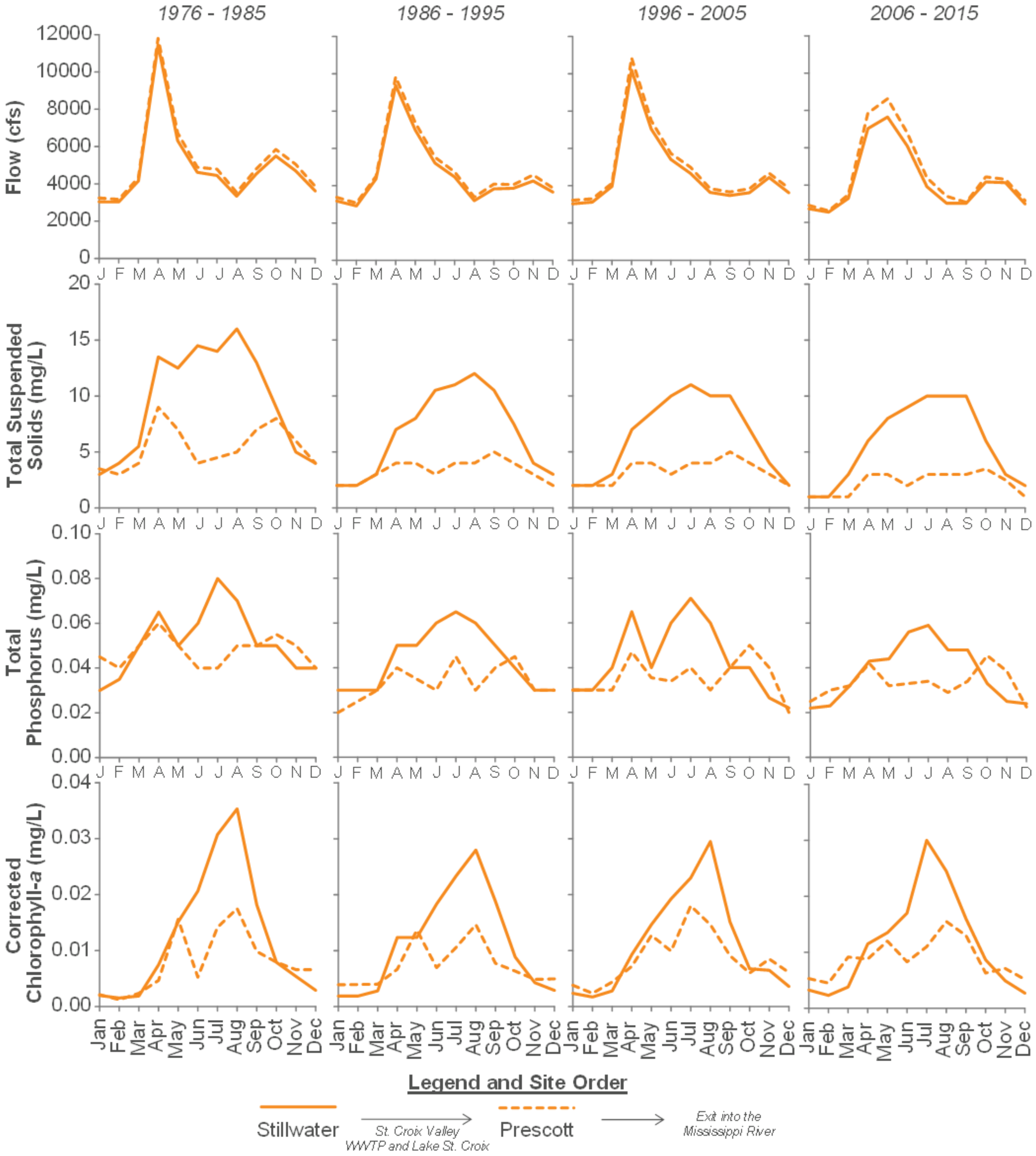


Figure 65. Long-Term Trend of St. Croix River Flow-Adjusted Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a*, 1976-2015

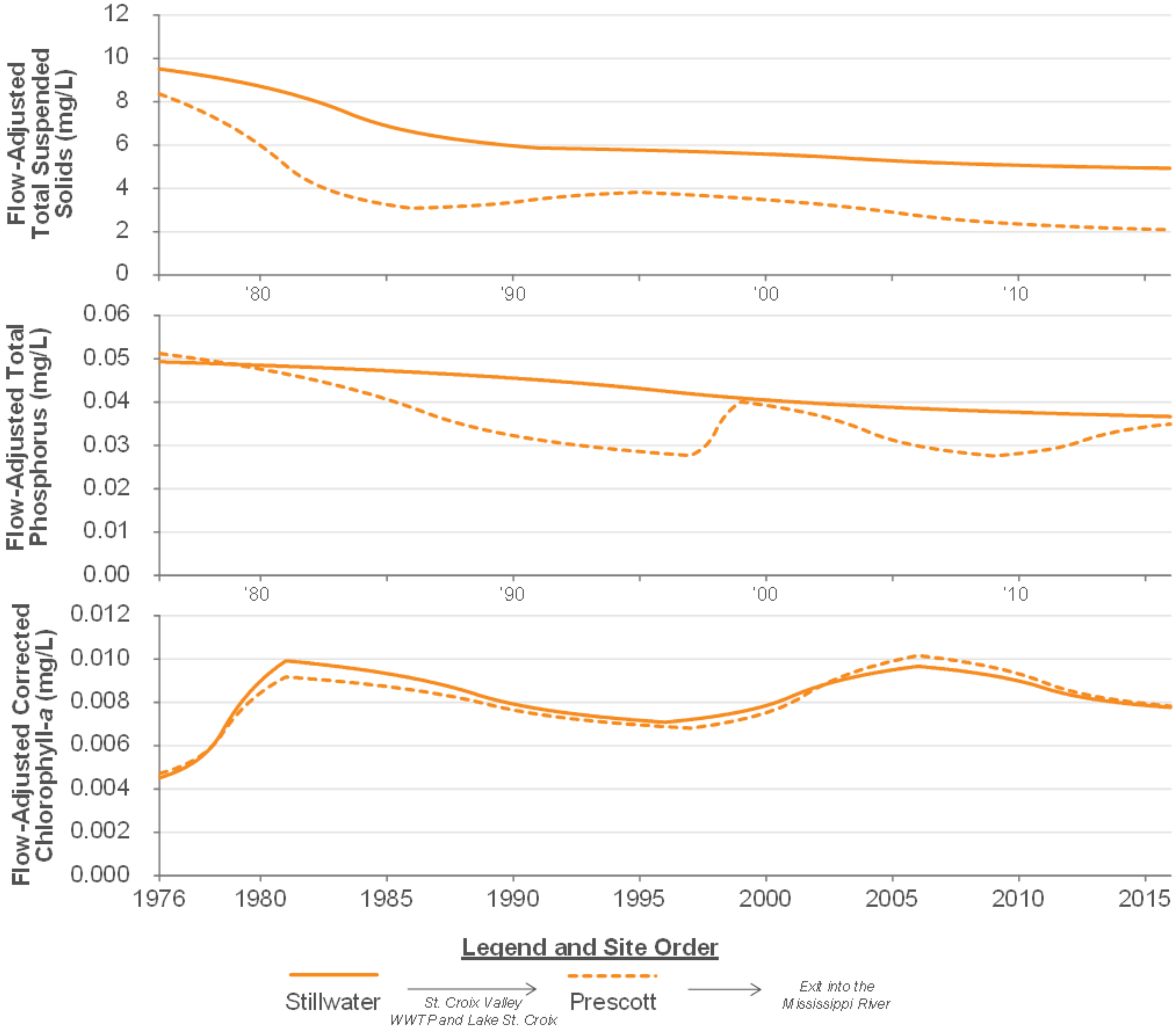


Table 19. Water Quality Trends of St. Croix River Flow-Adjusted Concentrations of Total Suspended Solids, Total Phosphorus, and Corrected Chlorophyll-*a*, 1976-2015

	TSS			TP			Chl-*a*		
		Flow-Adjusted Conc. (mg/L)			Flow-Adjusted Conc. (mg/L)			Flow-Adjusted Conc. (mg/L)	
Site	Overall Trend (%)	Start	End	Overall Trend (%)	Start	End	Overall Trend (%)	Start	End
Stillwater	-48	9.5	4.9	-26	0.049	0.037	72	0.004	0.010
Prescott	-75	8.4	2.1	-32	0.051	0.035	PT	-	-

PT – Partial Trend: One of the sub-trends within the trend model was not statistically significant, so a representative overall percentage change could not be calculated.

Total Nitrogen (TN), Nitrate-Nitrogen (NO_3), and Ammonia-Nitrogen (NH_3)

St. Croix River annual patterns for TN, NO_3, and NH_3 are presented in Figure 66, and monthly patterns by decade are presented in Figure 67. St. Croix River QWTREND results for TN, NO_3, and NH_3 are presented in Figure 68. Table 20 lists St. Croix River water quality trends for TN, NO_3, and NH_3, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 66. Annual Patterns of St. Croix River Median Flows and Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen, 1976-2015

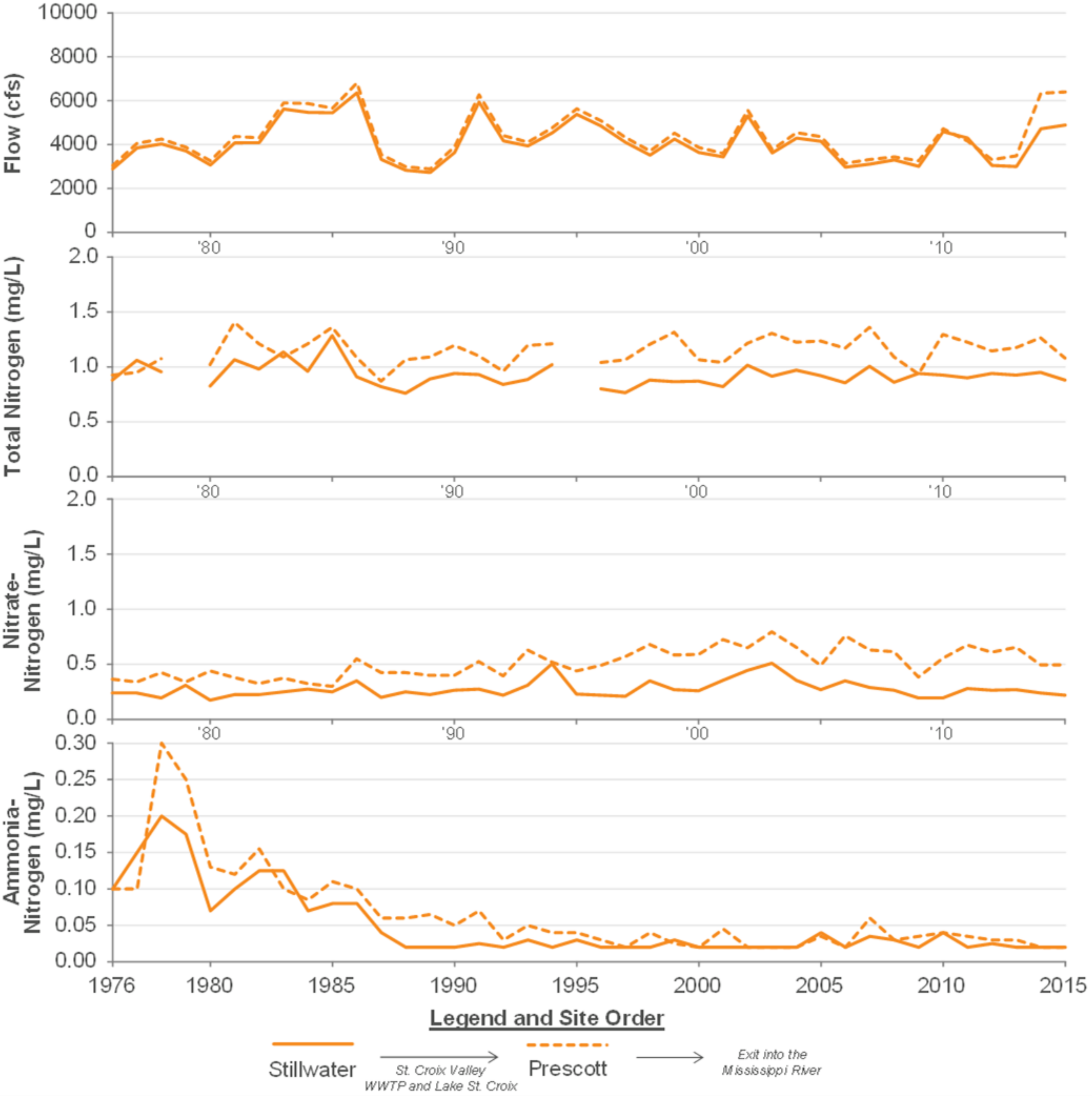


Figure 67. Monthly Patterns of St. Croix River Median Flows and Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen by Decade, 1976-2015

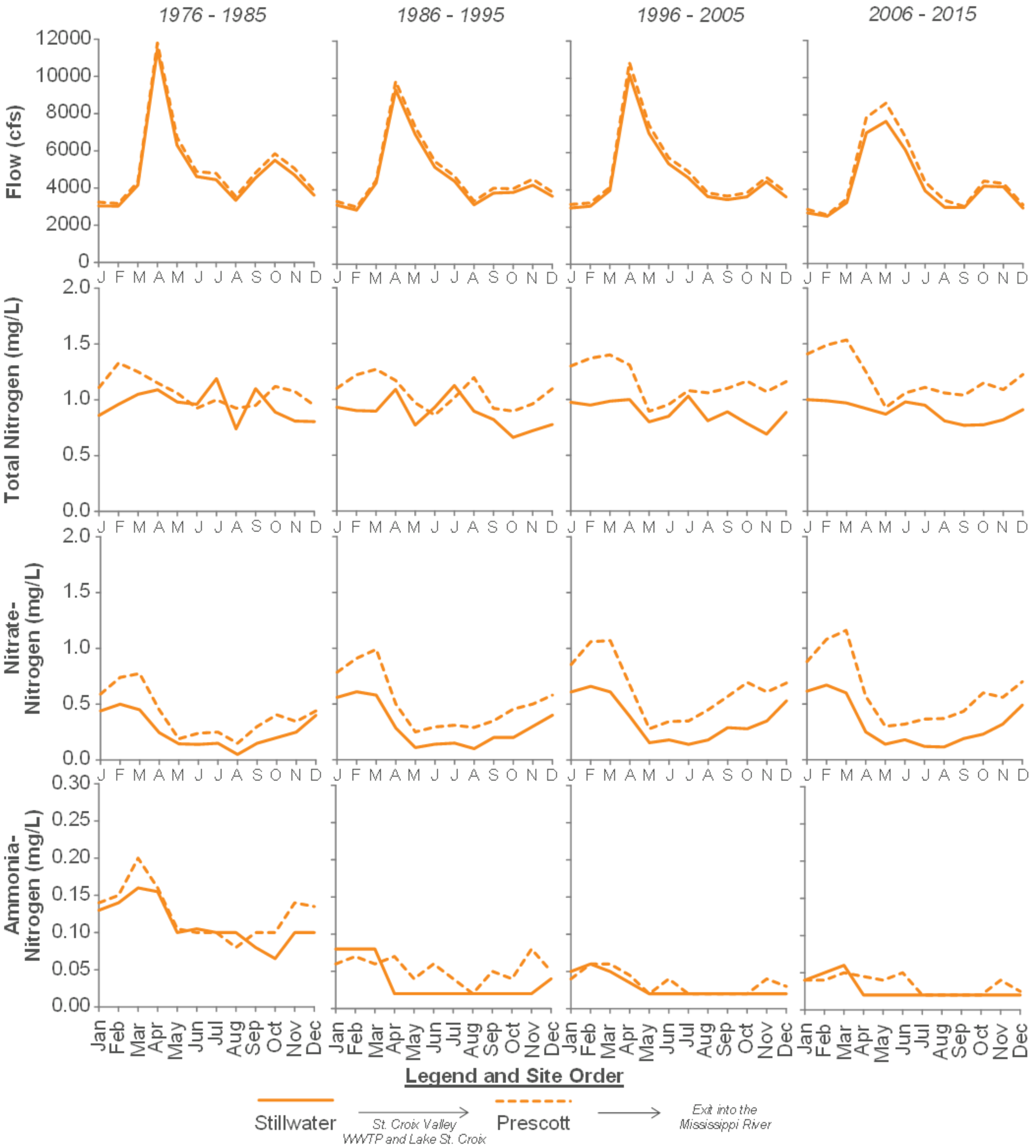


Figure 68. Long-Term Trends of St. Croix River Flow-Adjusted Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen, 1976-2015

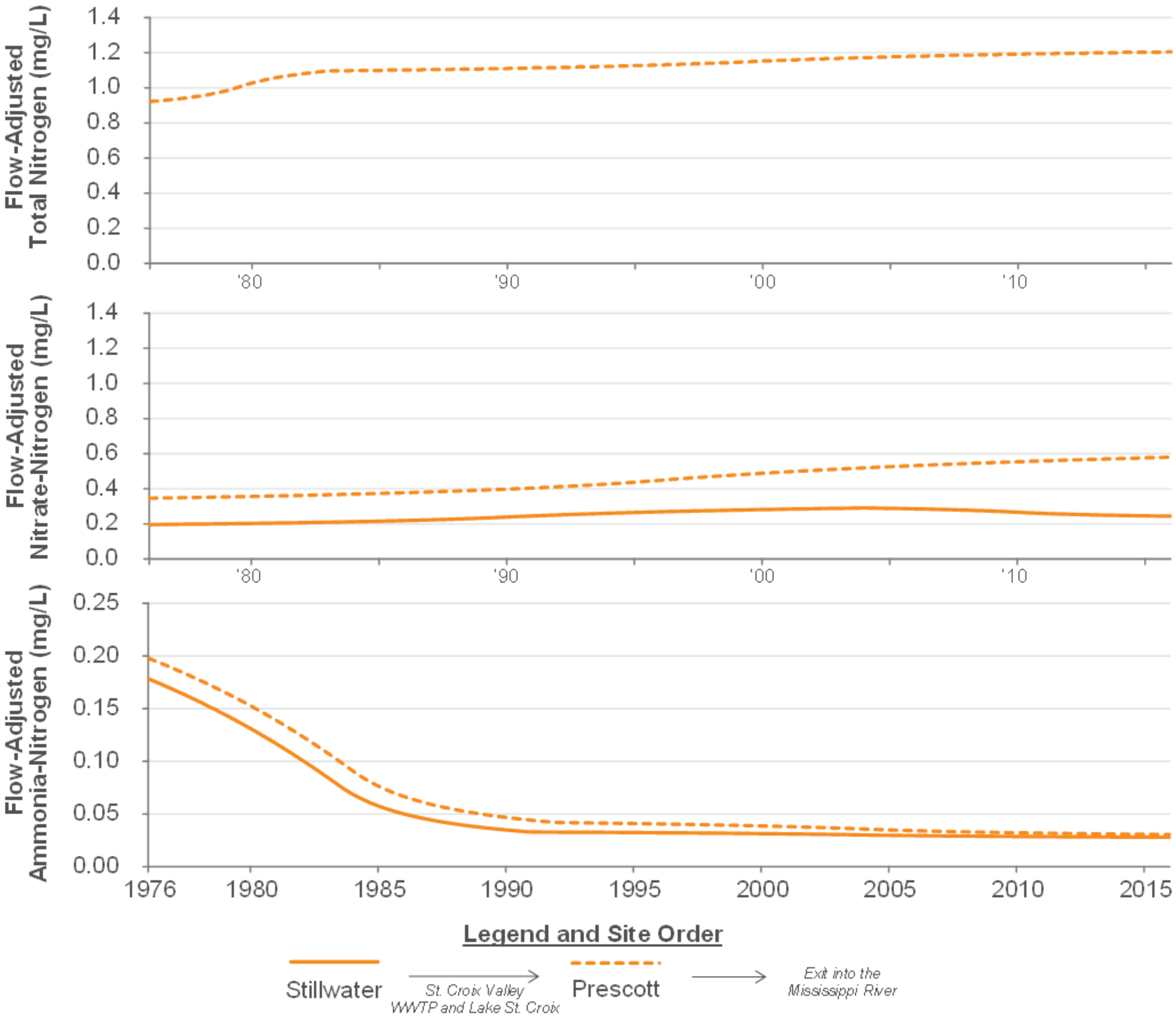


Table 20. Water Quality Trends of St. Croix River Flow-Adjusted Concentrations of Total Nitrogen, Nitrate-Nitrogen, and Ammonia-Nitrogen, 1976 to 2015

Site	TN			NO_3			NH_3		
	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)		Overall Trend (%)	Flow-Adjusted Conc. (mg/L)		Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End		Start	End		Start	End
Stillwater	NT	-	-	24	0.20	0.24	BRL	-	-
Prescott	31	0.9	1.2	67	0.35	0.58	BRL	-	-

NT- No Trend: A statistically significant trend model did not fit the data. Refer to the “Appendix” for more information on the non-significant Stillwater TN trend.

BRL - Below Reporting Limit: More than 10% of the data were below than the lab’s RL, so a representative overall percentage change could not be calculated.

Fecal Coliform (FC) and *Escherichia coli* (*E. coli*) Bacteria

St. Croix River annual patterns for FC and *E. coli* bacteria are presented in Figure 69, and monthly patterns by decade are presented in Figure 70. St. Croix River QWTREND results for FC bacteria are presented in Figure 71. Table 21 lists St. Croix River water quality trends for FC bacteria, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 69. Annual Patterns of St. Croix River Median Flows and Concentrations of Fecal Coliform and *E. coli*, 1976-2015

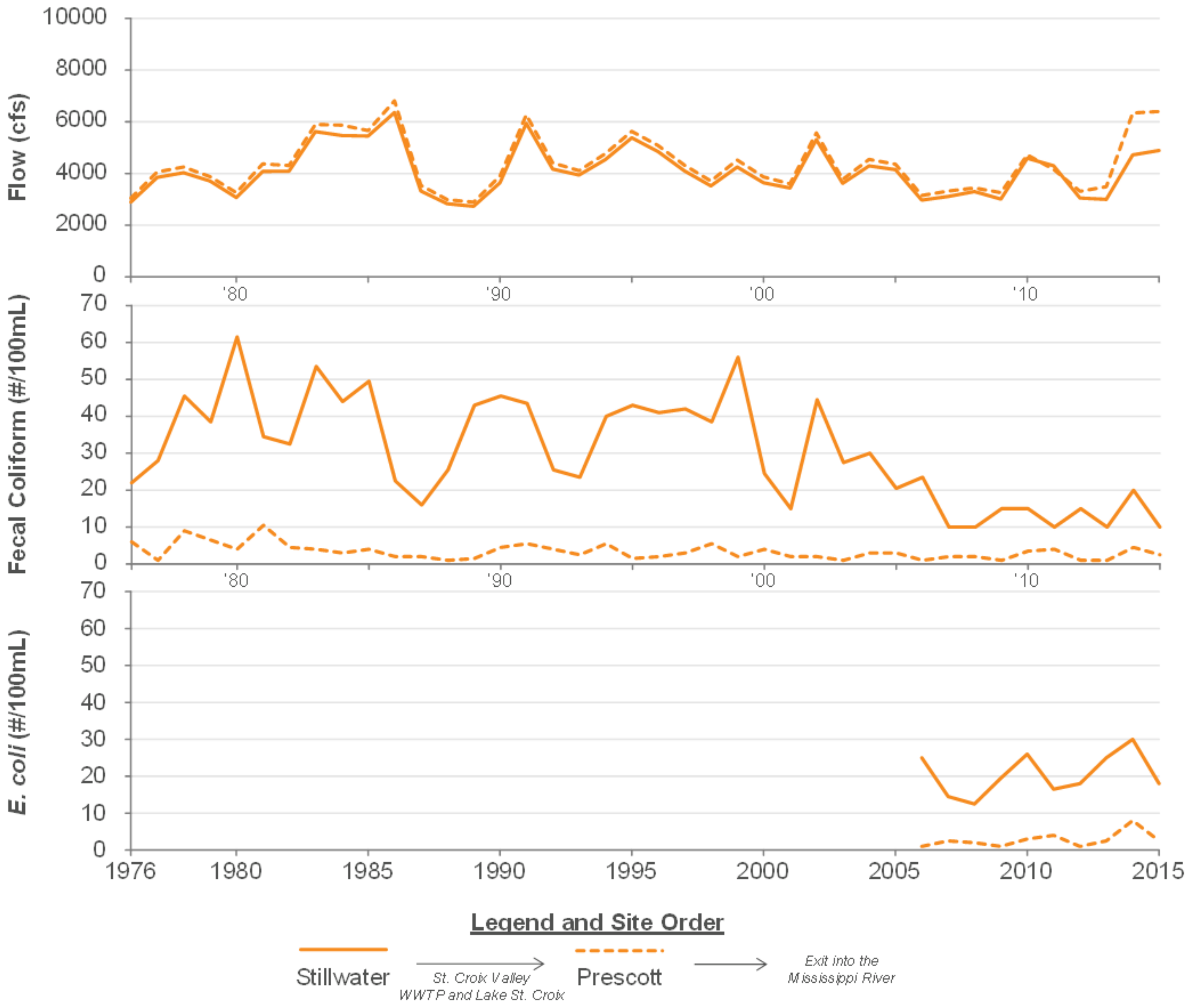


Figure 70. Monthly Patterns of St. Croix River Median Flows and Concentrations of Fecal Coliform and *E. coli* by Decade, 1976-2015

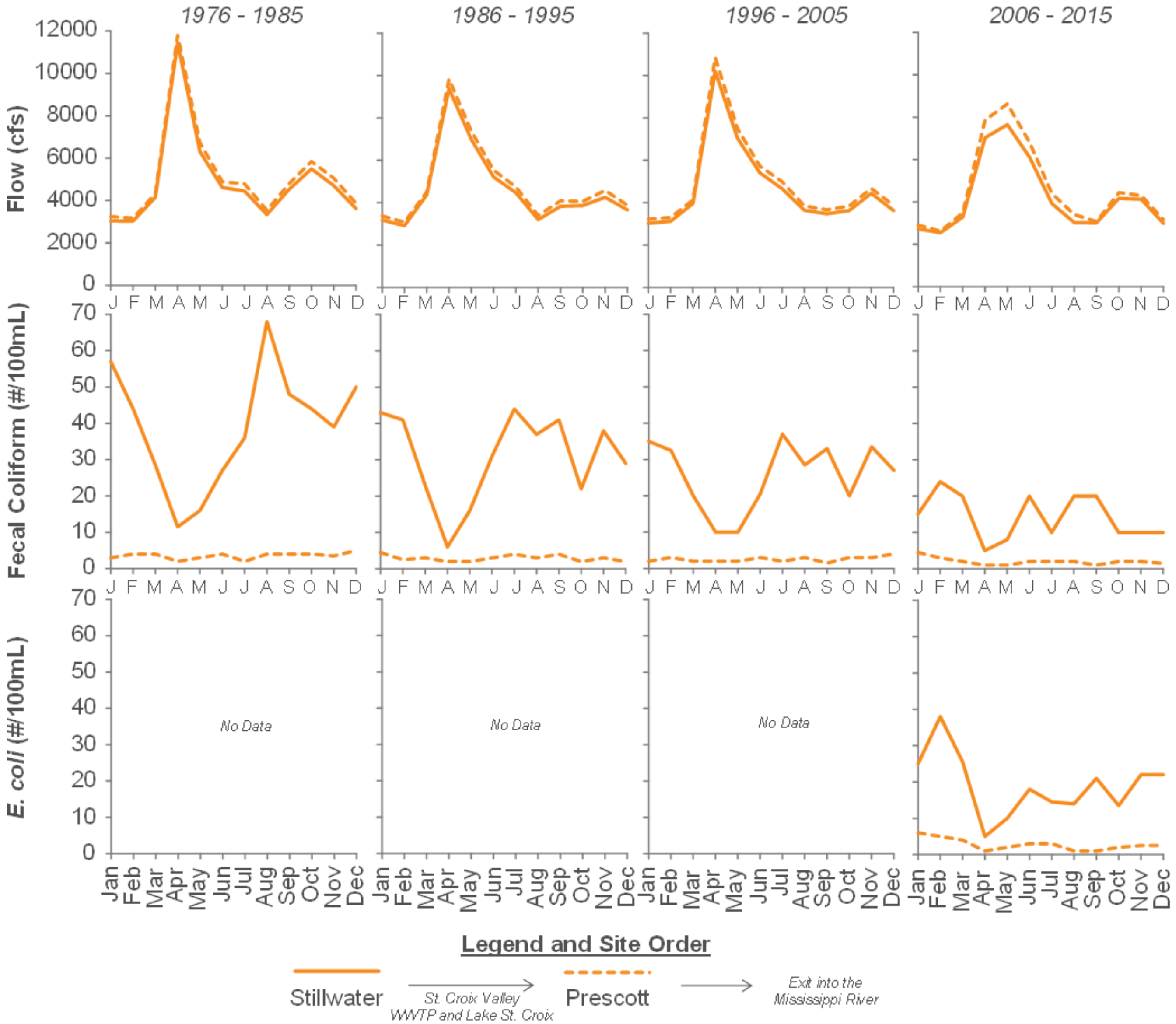


Figure 71. Long-Term Trends of St. Croix River Flow-Adjusted Concentrations of Fecal Coliform, 1976-2015

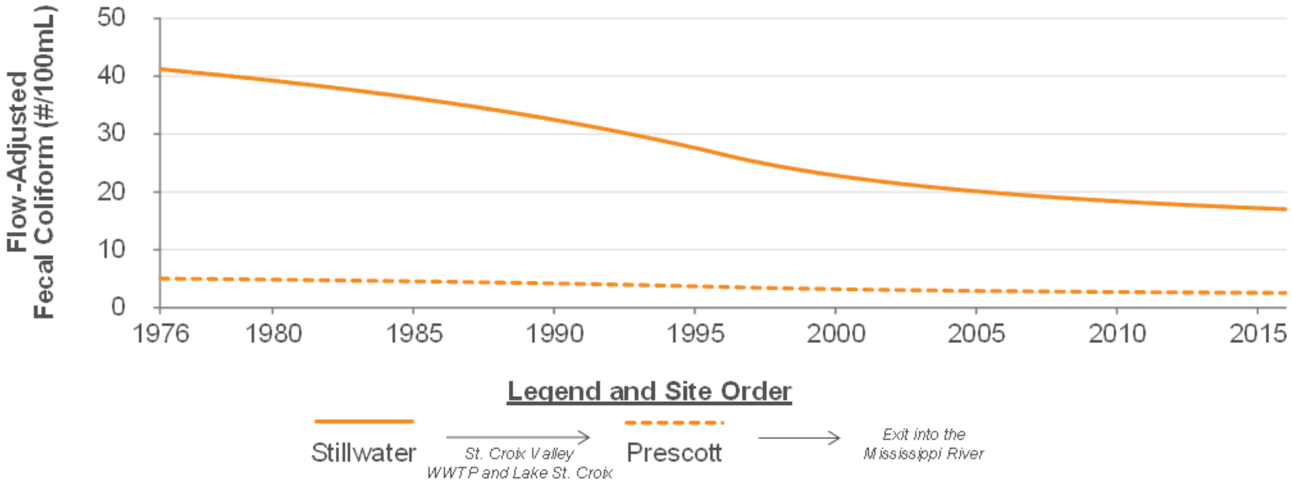


Table 21. Water Quality Trends of St. Croix River Flow-Adjusted Concentrations of Fecal Coliform, 1976-2015

Site	Overall Trend (%)	Flow-Adjusted Conc. (per 100 ml)	
		Start	End
Stillwater	-59	41	17
Prescott	BRL	-	-

BRL – Below Reporting Limit: More than 10% of the data are below than the lab's RL, so a representative overall percentage change could not be calculated.

Chloride (Cl)

St. Croix River annual patterns for Cl are presented in Figure 72, and monthly patterns by decade are presented in Figure 73. St. Croix River QWTREND results for Cl are presented in Figure 74. Table 22 lists St. Croix River water quality trends for Cl, including overall changes and modeled flow-adjusted concentrations at the start and end years.

Figure 72. Annual Patterns of St. Croix River Median Flows and Concentrations of Chloride, 1985-2015

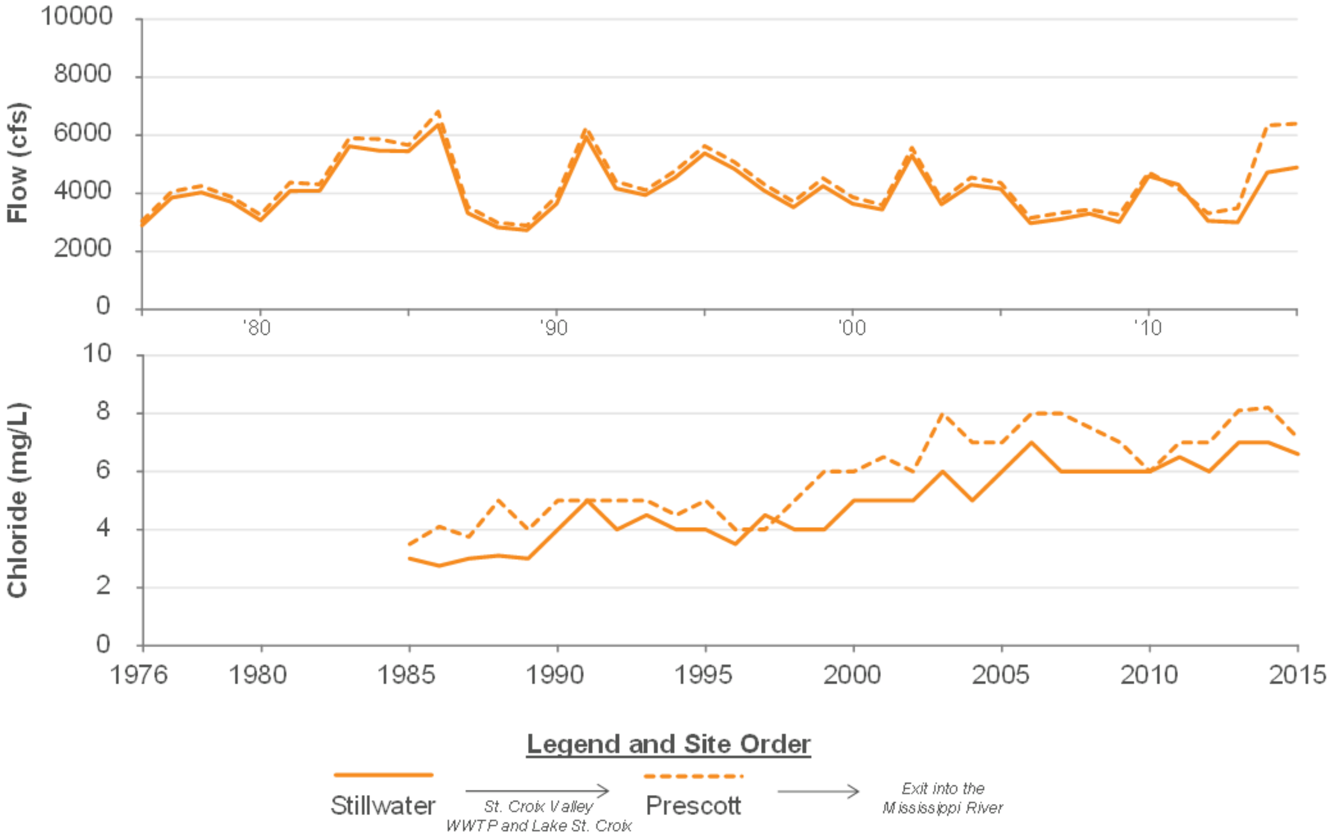


Figure 73. Monthly Patterns of St. Croix River Median Flows and Concentrations of Chloride by Decade, 1985-2015

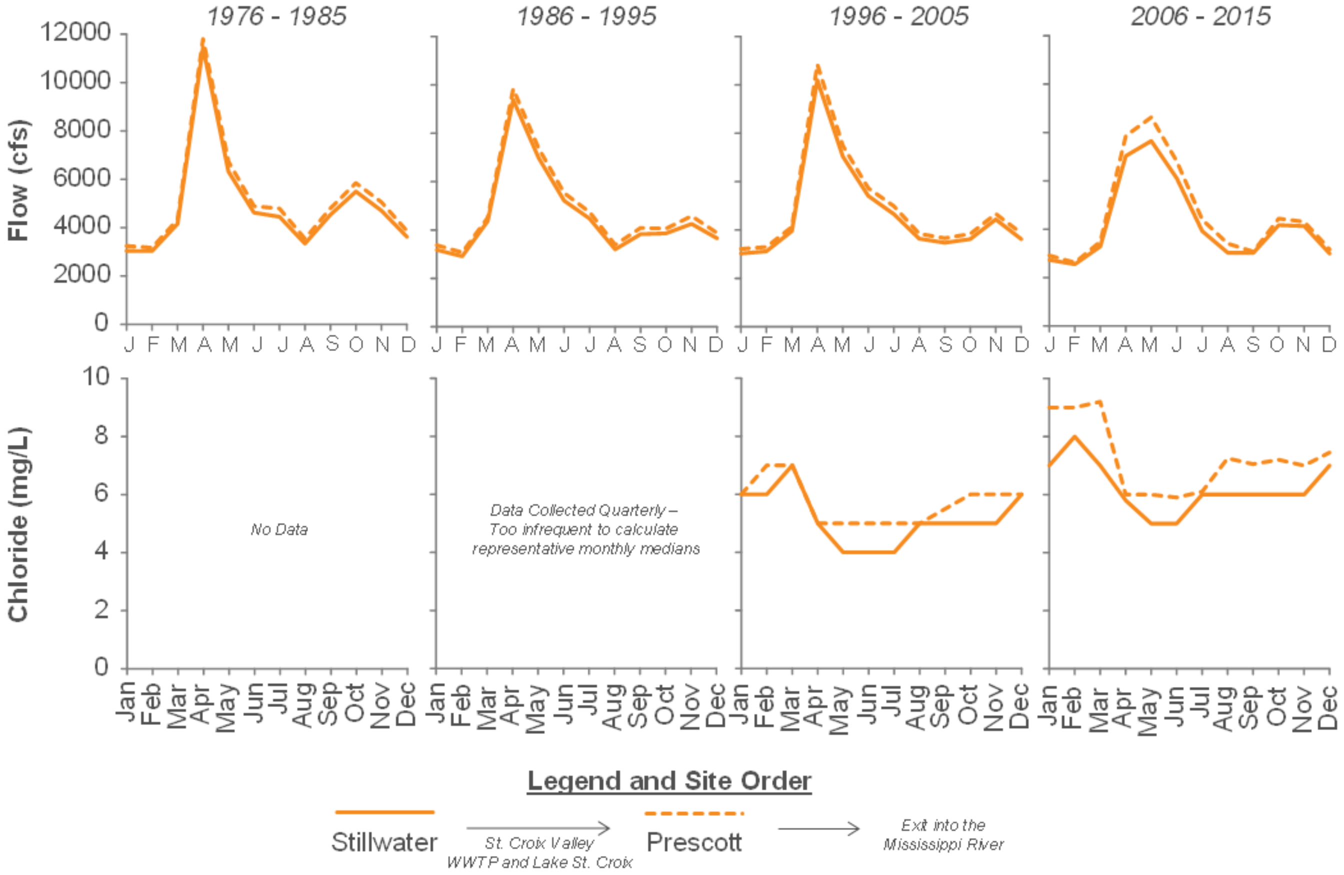


Figure 74. Long-Term Trends of St. Croix River Flow-Adjusted Concentrations of Chloride, 1985-2015

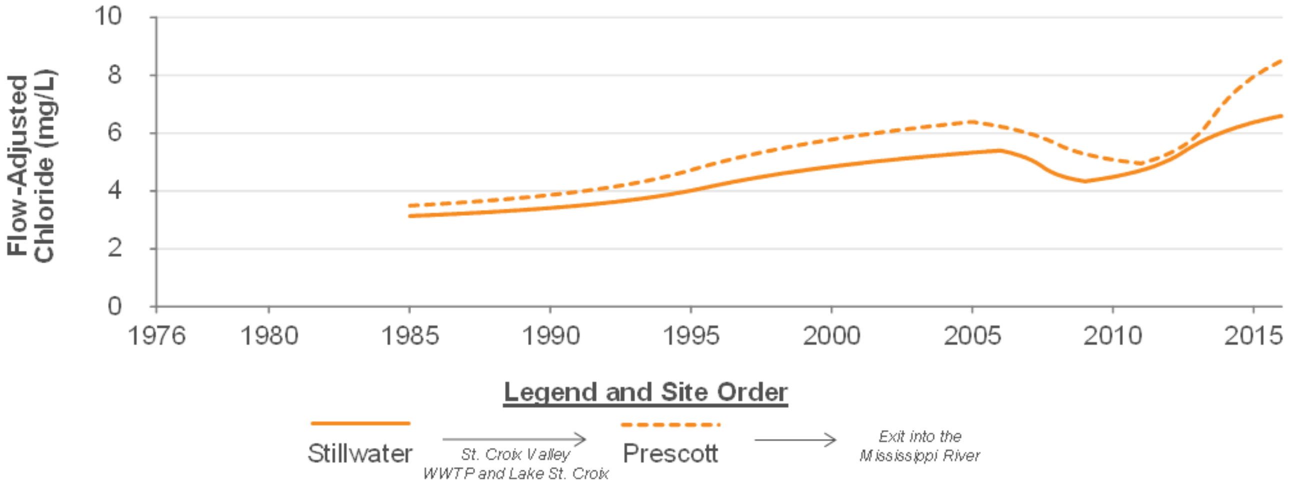


Table 22. Water Quality Trends of St. Croix River Flow-Adjusted Concentrations of Chloride, 1985-2015

Site	Overall Trend (%)	Flow-Adjusted Conc. (mg/L)	
		Start	End
Stillwater	110	3.1	6.6
Prescott	143	3.5	8.5

DISCUSSION

Rivers exhibit variations in water quality based on their watershed characteristics, both natural and human-influenced. Spatial changes in water quality occur along a river due to point and nonpoint sources of pollution, in-stream processes, and pollution control efforts. Comparing the results from the 10 monitoring locations on the Mississippi, Minnesota, and St. Croix rivers in the metro area provides a picture of water quality differences between these rivers, and how water quality changes as each river moves through the metro area.

This report section discusses recent regional river water quality, long-term water quality trends, spatial patterns in water quality, and potential reasons for water quality patterns and trends. The discussion of each water quality parameter is structured around two styles of regional maps.

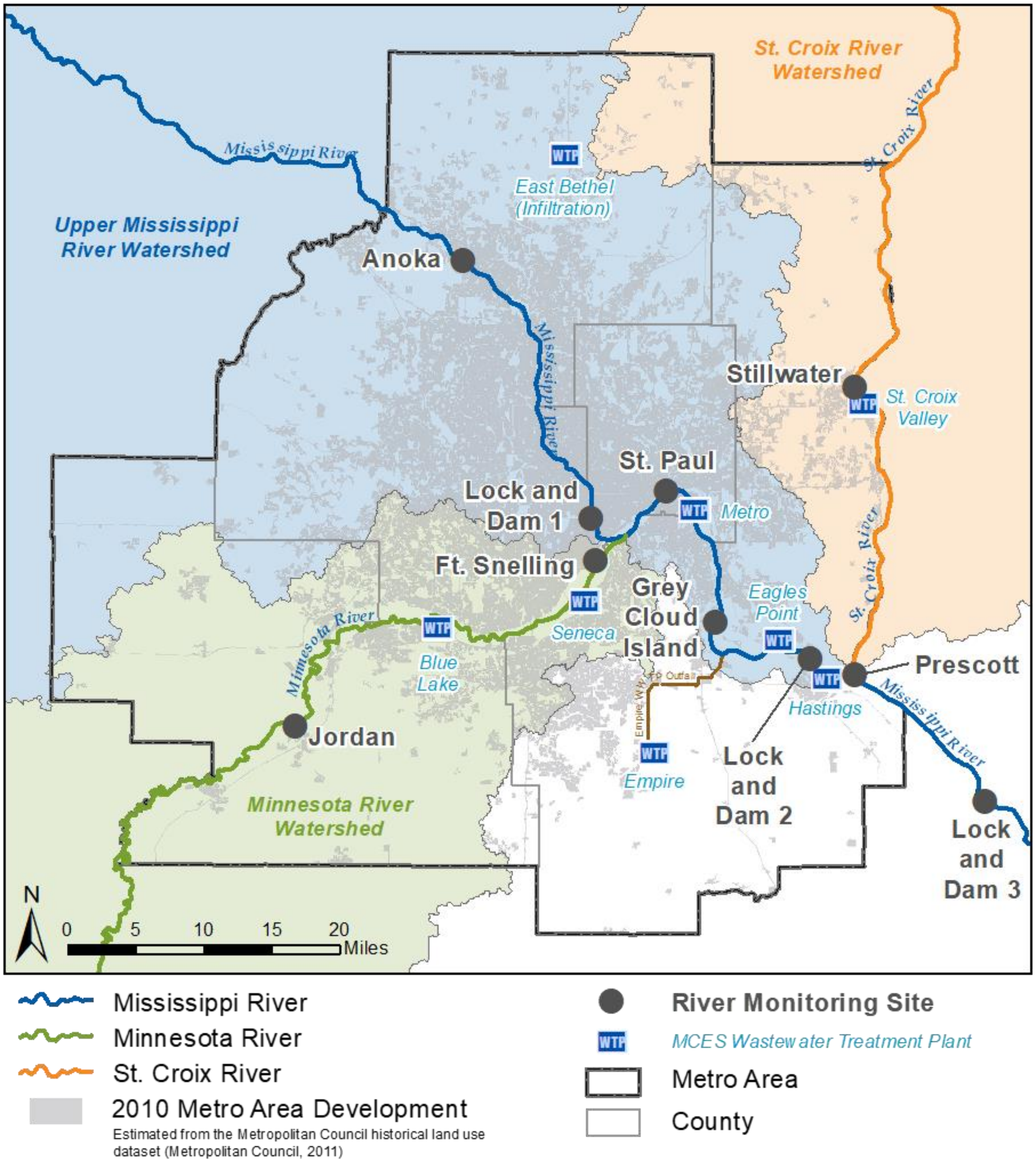
The first type of map represents the most recent (2006-2015) water quality conditions in metro area rivers. The 10-year median concentrations of each water quality parameter are plotted at the 10 monitoring sites, using circle sizes that are proportional to the 10-year median concentrations. These maps can be used to understand water quality differences between the three rivers and how water quality changes as the rivers flow through the metro area.

For those water quality parameters that were analyzed for long-term (1976-2015) trends using QWTREND, the second type of map displays the trend directions and percentage changes in flow-adjusted concentrations of each water quality parameter at the 10 monitoring sites. The shape of the trend line at each monitoring site is also depicted, although for display purposes the trend shapes may be scaled differently (refer to “Results” to view the accurate magnitudes of the trendlines plotted on a y-axis). The percent changes in flow-adjusted concentrations were calculated based on statistically significant trends analyzed using QWTREND. The long-term trend results are very useful for understanding temporal changes in river water quality and linking those changes to regional impacts and pollution control efforts. There were three situations in which an overall percentage change could not be calculated for a trend. The first situation was when a statistically significant trend model did not exist, referred to as “No Trend” (NT). The second situation was when at least one sub-trend within a significant trend model was not statistically significant, referred to as a “Partial Trend” (PT). The third situation occurred when more than 10% of the data were less than the analytical laboratory’s reporting limit, referred to as “Below Reporting Limit” (BRL). Even though the overall change could not be calculated for PT and BRL results, the shape and direction of the trends were still reported as an exploratory result to determine if an overall increasing or decreasing trend was apparent.

QWTREND is a multiple trend model which can show how the direction and slope of a trend changes throughout the 40-year assessment period. However, this level of detail is not reflected in the summary maps included in this section. Therefore, when the sub-trends within the overall trend assessment period provide notable information, they are included as a part of the discussion. The detailed sub-trend results are displayed in the “Appendix”.

For reference, Figure 75 shows the metro area Mississippi, Minnesota, and St. Croix rivers and their watersheds, the 10 monitoring sites on these rivers, and the locations of MCES WWTPs.

Figure 75. Metro Area Mississippi, Minnesota, and St. Croix Rivers and Watersheds, River Monitoring Sites, and MCES Wastewater Treatment Plants



Estimated from the Metropolitan Council historical land use dataset (Metropolitan Council, 2011)

Recent Water Quality Conditions and Long-term Water Quality Trends by Parameter

Flow

Flow has a considerable influence on the water quality of a river. High flows often reflect delivery of pollutants from the watershed, while low flows can amplify point sources of pollution, when less water is available to provide a dilution effect. The amount and timing of precipitation in a watershed are the main factors affecting flow in streams and rivers (USGS, 2016a). Other watershed factors such as soil characteristics, soil saturation, land cover, artificial drainage, and slope of the land affect how much of the water either infiltrates into the ground, evaporates, transpires from plants, or runs directly into surface waters (USGS, 2016a).

Physical changes in a watershed affect runoff to streams and rivers, which can impact overall flow. The characteristics of urban development, such as altered landscapes, impervious surfaces, and artificial drainage networks, result in increased runoff into surface waters when precipitation occurs (USGS, 2003). Agricultural land has a similar effect; increases in stream and river flows are associated with the conversion of perennial vegetation to seasonal row crops and the artificial drainage of agricultural fields (Lenhart et al., 2011; Raymond et al., 2008; Schilling and Helmers, 2008; Schottler et al., 2013; Zhang and Schilling, 2006). Modifications within a river itself, such as navigation channels and impoundments like locks and dams, can also impact river flow.

Recent Conditions. Figure 76 shows the median flows measured as cubic feet per second (cfs) from 2006-2015 at river monitoring sites in the metro area. Entering the metro area, the Mississippi River had the highest 10-year median flow. The median flow of the St. Croix River was slightly higher than that of the Minnesota River. The Mississippi, Minnesota, and St. Croix rivers contributed 46%, 25%, and 29%, respectively, of the total incoming median flow. In all three rivers, flow increased as the rivers moved through the region, reflecting contributions from tributaries and point sources. Notable increases in Mississippi River flow occurred downstream from the Minnesota and St. Croix River confluences.

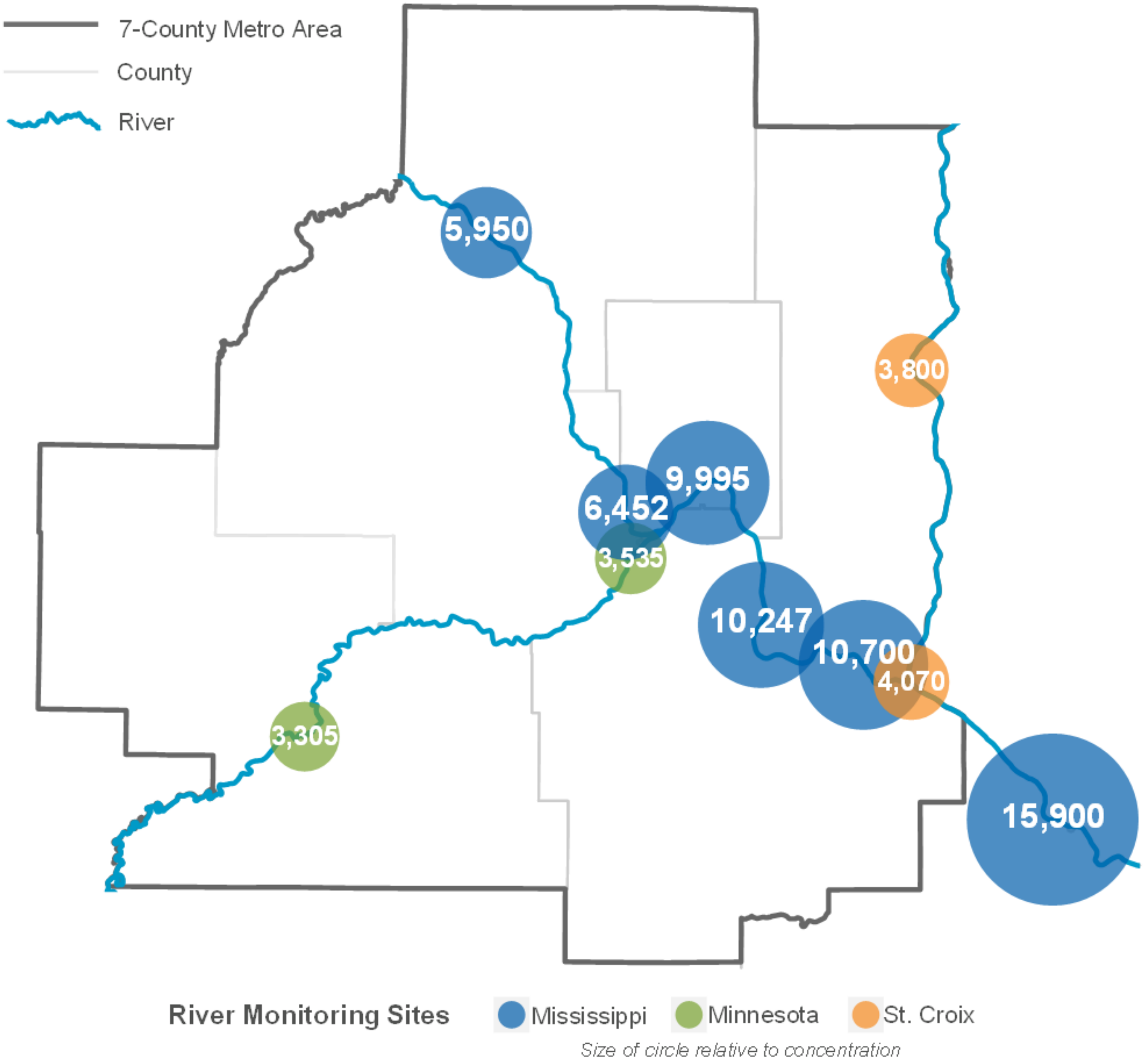
Flow contributions from MCES WWTPs were a minimal contribution under typical conditions. The 10-year median flow of the Metro WWTP was 266 cfs, which is just 3% of the median Mississippi River flow at Saint Paul. Median flows from the Blue Lake and Seneca WWTPs were 40 and 34 cfs, respectively. Combined, the median flow of these two WWTPs was just 2% of the median Minnesota River flow at Jordan. Since flows from MCES WWTPs are generally constant, they contribute a larger proportion of the river flow during low flow conditions and a smaller proportion during high river flow conditions.

Trends. Flow trends were not evaluated in this study because QWTREND is a flow-adjusted model. However, other studies have shown that flows in the Mississippi, Minnesota, and St. Croix rivers have been increasing (MPCA, 2017b; USGS, 2004; Zhang and Schilling, 2006; Lafrancois et al., 2013). Increased river flows can trigger water quality issues, such as increased erosion and a greater susceptibility to runoff pollution (MPCA, 2017b).

Typically, climate change, urbanization, and agricultural practices are the factors identified as the cause of the increasing river flows. Novotny and Stefan (2007) found trends of increasing streamflow in many Minnesota rivers over the 1973-2002 period. They documented a strong correlation between precipitation and streamflow, but also noted the potential contributions of urbanization and agricultural drainage to increased streamflow. The conversion from perennial to seasonal row crops and the use of artificial agricultural drainage have both been linked to increasing flows (Shilling and Helmers, 2008;

Zhang and Schilling, 2006). Between precipitation changes, conversion of crops, and artificial drainage, Schottler et al. (2013) identified artificial drainage of agricultural fields as the largest driver of increasing river flows in Minnesota.

Figure 76. Median Flow (cfs) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



Dissolved Oxygen (DO)

DO is the amount of oxygen dissolved in a sample of water, and it can be a useful indicator of water quality. Sufficient oxygen levels in water are necessary for a healthy river ecosystem, while low oxygen levels can be fatal to aquatic organisms and result in a degraded habitat (MPCA, 2009b). The amount of oxygen in water depends on factors such as water temperature, biological activity (photosynthesis and respiration), atmospheric pressure, concentrations of dissolved materials, proportion of groundwater flow, stream morphology, and the flow regime.

In recent years, low DO concentrations are most often caused by excessive algae growth due to high availability of nutrients (MPCA, 2009b). The algal matter increases biochemical oxygen demand (BOD), and DO concentrations decrease as oxygen is consumed when algae die and decompose. Reduction of phosphorus and BOD pollution is a common strategy to limit excess algae growth and prevent harmfully low DO conditions (MPCA, 2004a; 2005).

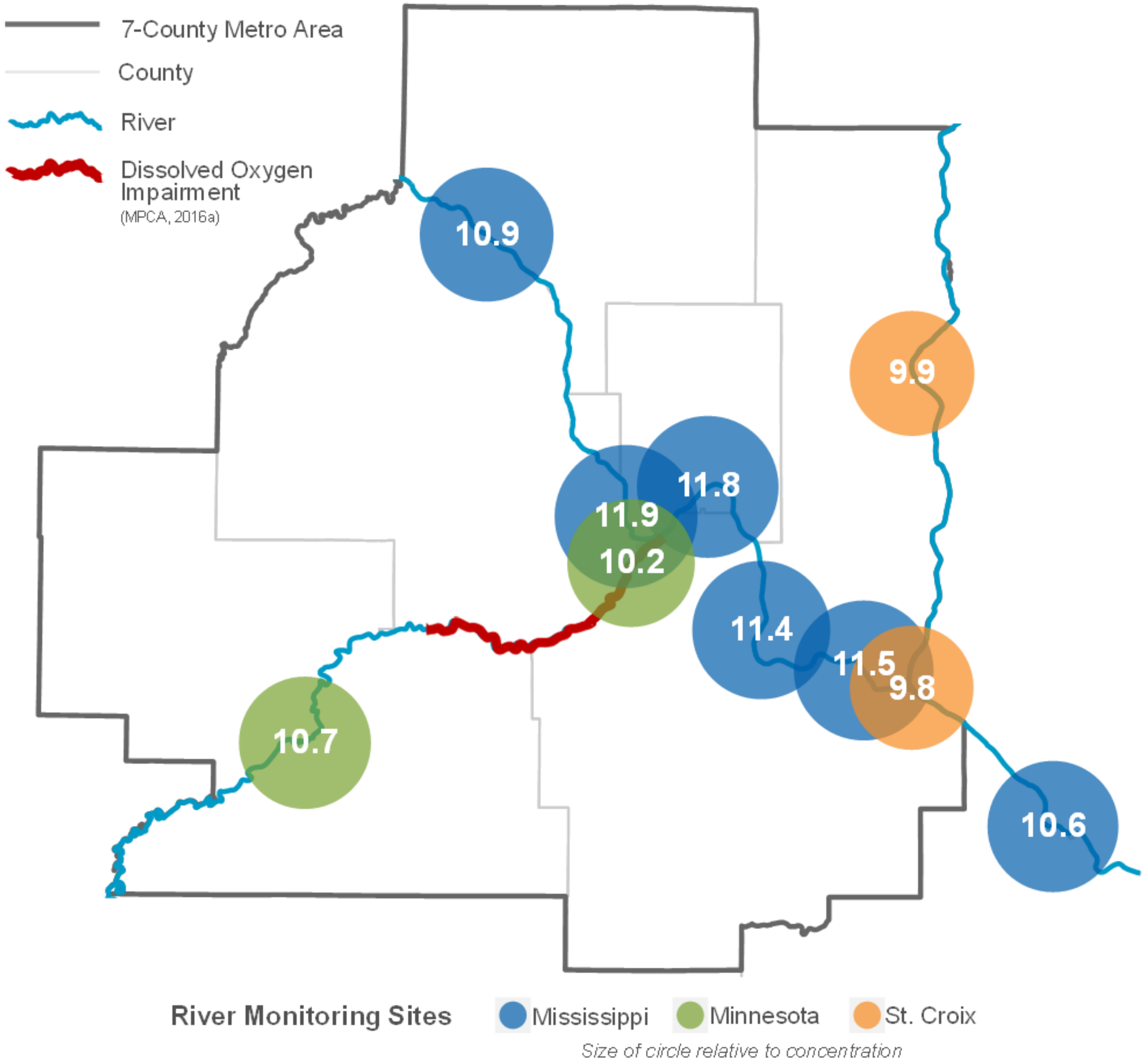
Recent Conditions. Figure 77 shows the median DO concentrations measured from 2006-2015 at river monitoring sites in the metro area. The 10-year median concentrations were similar at all sites, indicating that oxygen dynamics were comparable along all three rivers. However, the median concentrations did not capture minimum DO concentrations or the duration of such events, which pose the highest risk to aquatic organisms. Additionally, the data used in this report were generally collected in the morning on a set rotation of monitoring sites, so some sites were typically sampled earlier in the day than others. This is not an issue for most parameters but can create a bias in the results for parameters that have a 24-hour (diel) cycle. DO concentrations generally exhibit a daily pattern due to changes in temperature (USGS, 2017) and river metabolism, that is, the alternating pattern of photosynthesis during the day and respiration at night (Guasch et al., 1998; Mulholland et al., 2005). For this reason, care should be taken when interpreting any differences in the median DO concentrations between sites in Figure 77. A study using DO measurements taken at comparable times of the day from each monitoring site would be needed to look at the differences between sites without the potential influence of varying sampling times.

Physical features in the rivers, such as spillways over dams, can cause flow turbulence that oxygenates the water, thereby affecting DO concentrations. Algal growth and biological activity likely impacted oxygen dynamics as the rivers moved through the region, potentially due to a variety of factors such as changes in flow and river morphology, nutrient inputs, and light availability.

In most cases, median DO concentrations decreased between upstream and downstream sites in the three rivers. Although this could have been due in part to differences in sampling times, other studies have also noted decreases in DO concentrations as the Minnesota River flowed through the metro area (MCES, 2010; MPCA, 2004a). These reduced DO concentrations may be attributed to the more lake-like conditions in the lower Minnesota River, in Pool 2 of the Mississippi River, and in Lake St. Croix. The reduced water velocities in the lower Minnesota River and Mississippi River are caused by the deeper navigation channel and pool-like effect created by Lock and Dam 2 (MPCA, 1985; MPCA, 2004a). Slower water velocity and increased water residence time cause algae in the river to die and decay, consuming oxygen in the process (MPCA, 2004a). Specifically, MCES (2010) has suggested that the slow-moving waters may cause the algae to settle out of the photic zone and die due to insufficient light availability.

The 10-year median DO concentration in the Metro WWTP discharge was 5.1 mg/L (MCES unpublished data accessed Dec. 2017), approximately 40% of the median DO concentration in the Mississippi River at Saint Paul. Low DO concentrations can result from high BOD_5 concentrations, which are often caused by WWTP discharges and excessive algae growth due to high phosphorus concentrations. As such, BOD_5 and phosphorus are the pollutants targeted to maintain adequate DO concentrations (MPCA, 2004a). As noted below in their respective sections, BOD_5 and TP concentrations in MCES WWTP discharges have been markedly reduced by implementing secondary and advanced secondary treatment, including Bio-P technology for phosphorus reduction. However, controlling BOD_5 and phosphorus pollution from other sources besides WWTPs is also important to prevent decreases in DO concentrations (MPCA, 2003).

Figure 77. Median Dissolved Oxygen Concentrations (mg/L) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



The Minnesota water quality standard for DO requires a daily minimum concentration of 5.0 mg/L (Minn. Rules Chapter 7050). Based on this standard, the MPCA has determined that the lower 22 miles of the Minnesota River (including the monitoring station at Fort Snelling) are impaired due to low DO concentrations (MPCA, 2016a). This impairment exists because of the high BOD_5 concentrations created by excess phosphorus and algae during low flow conditions (MPCA, 2004a).

Trends. QWTREND was not used to investigate long-term trends in DO concentrations because of the potential biases caused by sampling schedules and diel variations in DO concentrations. Although different trend assessment techniques were used, past studies have found small increasing trends in DO concentrations at regional river monitoring sites (Table 23).

Table 23. Results from Past Studies of Dissolved Oxygen Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers

Author	Study Period	Trend Analysis Method	Anoka	Lock and Dam 1	Saint Paul	Grey Cloud Island	Lock and Dam 2	Jordan	Fort Snelling	Stillwater
MCES 2004	1976-2002	SEAKEN	NT					NT		4%
Lafrancois 2013	1976-2005	SEAKEN	NT	NT	5%	10%	7%		13%	

SEAKEN: nonparametric Seasonal Kendall test
NT: no significant trend

5-Day Biochemical Oxygen Demand (BOD_5)

BOD_5 concentration is a measurement of the amount of dissolved oxygen that microorganisms use to decompose the organic matter in a water sample during a 5-day period. A higher BOD_5 concentration indicates more organic material in the water, which comes from sources including leaves, woody debris, dead organisms, manure, wastewater discharges, feedlots, failing septic systems, and urban stormwater runoff (USEPA, 2012b). Excessive organic matter (and high BOD_5 concentrations) can cause low dissolved oxygen (DO) concentrations in water bodies, which negatively impacts aquatic life. Elevated BOD_5 concentrations often correlate with the presence of chlorophyll and nutrients, since nutrients can lead to increased algal growth in summer months, requiring oxygen to break down the dead algal material (Heiskary and Markus, 2001).

Recent Conditions. Figure 78 displays the median BOD_5 concentrations measured from 2006-2015 at river monitoring sites in the metro area. As the rivers entered the metro area, the 10-year median BOD_5 concentration was highest in the Minnesota River (2.4 mg/L), lowest in the St. Croix River (1.2 mg/L), and intermediate in the Mississippi River (1.8 mg/L). As noted later, the Minnesota River also had the highest 10-year median concentrations of nutrients (TP - Figure 87, TN - Figure 93, NO_3 - Figure 95) and Chl-*a*, (a proxy for the amount of algae, Figure 91). Past studies have shown that BOD_5 concentrations correlate with nutrients and Chl-*a* in Minnesota's rivers, and the amount of both living and dead algae increases the overall oxygen demand (Heiskary and Markus, 2001).

The 10-year median BOD_5 concentration increased in the segment of the Minnesota River between Jordan to Fort Snelling as it flowed through the metro area, indicating an increased amount of organic material in the water. Most of the oxygen demand in the lower Minnesota River comes from the decomposition of excess algae, which grows upstream due to high phosphorus concentrations, then is transported downstream. This effect is amplified during low flow conditions (MPCA, 2003; 2004a). In the St. Croix River, the BOD_5 concentration decreased slightly from the upstream site (Stillwater) to the downstream site (Prescott). More than 10% of the BOD_5 concentrations at Stillwater and Prescott were less than the historical analytical RL (1.0 mg/L), but these values were represented as 1.0 mg/L to calculate the 10-year median concentrations. As such, the true 10-year median BOD_5 concentrations at Stillwater and Prescott are lower than those shown in Figure 78.

As the Mississippi River flowed through the metro area, the confluence of the Minnesota River caused a higher median BOD_5 concentration at Saint Paul compared to other upstream Mississippi River sites. Conversely, the St. Croix River provided a dilution effect that contributed to a lower BOD_5 concentration at Lock and Dam 3.

The three major MCES WWTPs in the metro area did not appear to influence the recent 10-year median BOD_5 concentrations in the Mississippi and Minnesota rivers. For example, the Mississippi River BOD_5 concentration was 1.9 mg/L both above and below the Metro WWTP at Saint Paul and Grey Cloud Island, respectively. Compared to these Mississippi River BOD_5 concentrations, the 10-year median BOD_5 concentration in the Metro WWTP discharge was 2.5 mg/L, with the Metro WWTP median flow contributing only 3% of the median Mississippi River flow during the past 10-year period (MCES unpublished data accessed Dec. 2017). Similarly, the 10-year median BOD_5 concentrations in the Blue Lake and Seneca WWTP discharges were both 2.0 mg/L, with these WWTPs combining to contribute only 2% of the median Minnesota River flow during the past 10-year period (MCES unpublished data accessed Dec. 2017).

Eutrophication impairments in rivers are evaluated by the MPCA using criteria for TP (the causative variable) and Chl-*a*, BOD_5, diel DO flux, and pH (the response or stressor variables) (Minn. Rules Chapter 7050; MPCA, 2015d). A eutrophication impairment exists if the criterion for TP, as well as the criteria for one or more of the response criteria, are exceeded. The criteria are based on multi-year summer averages of the parameter concentrations. The criteria for the response variable BOD_5 at metro area river monitoring sites are listed in Table 24. In the Mississippi River navigation pools, the only response variable considered is Chl-*a*, so there are no BOD_5 criteria for any of the Mississippi River sites except that at Anoka. Similarly, Lake St. Croix is evaluated as a lake instead of a river, and the only response criteria considered in the lake eutrophication standard are Chl-*a* and Secchi disk transparency (Heiskary and Wilson, 2008). As a result, there are also no BOD_5 criteria for the St. Croix River sites. Regardless, since the eutrophication criteria are based on multi-year summer average concentrations, the median BOD_5 concentrations in Figure 78 are not comparable to the criteria in Table 24. As shown in Figure 78, seven of the ten river monitoring sites are on river reaches with eutrophication impairments (MPCA, 2016a).

Figure 78. Median BOD_5 Concentrations (mg/L) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015

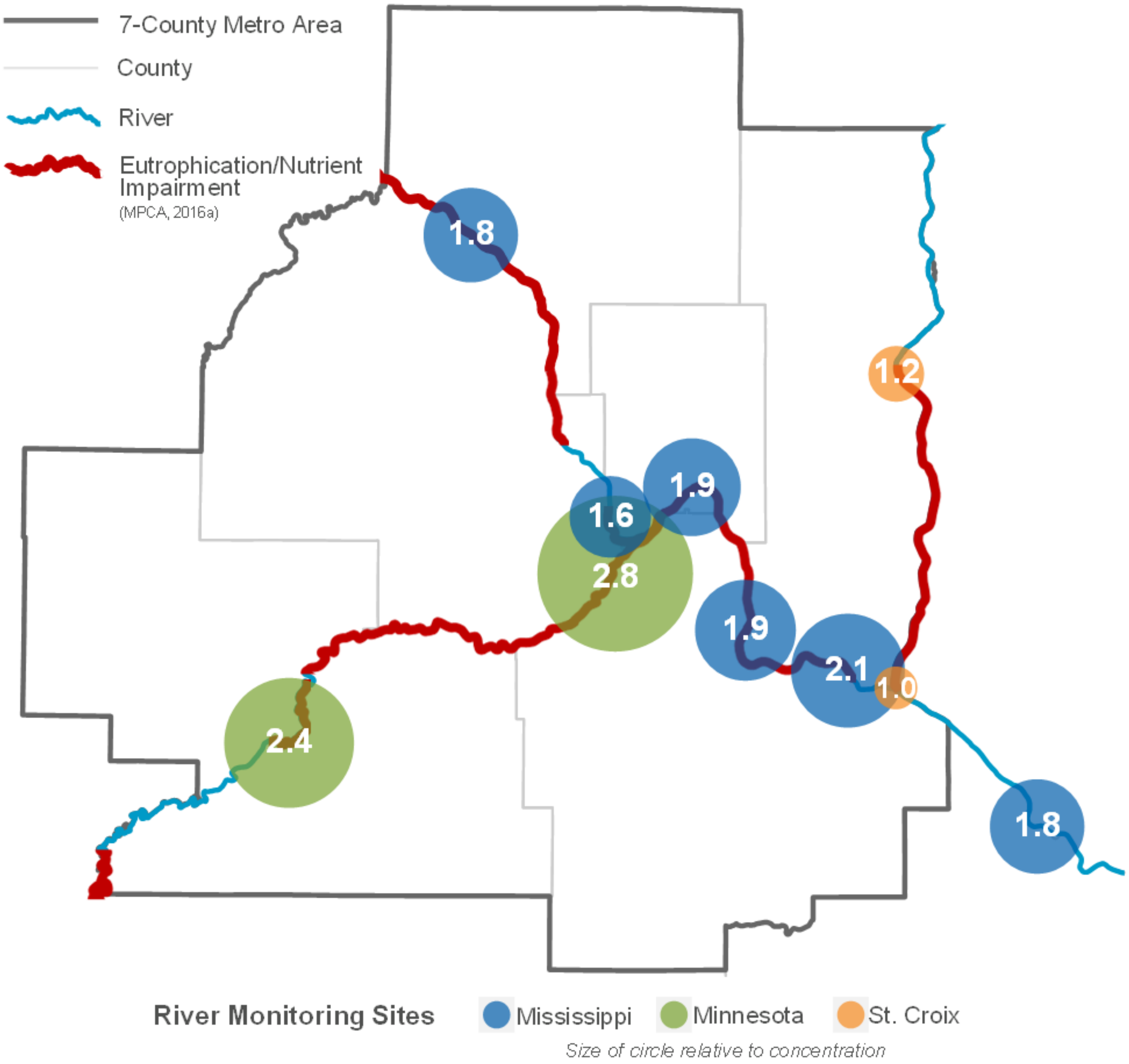


Table 24. Eutrophication Criteria at Metro Monitoring Sites - BOD_5

Site	BOD_5 Criteria (mg/L) [a]
Mississippi River	
Anoka	2.0
Lock and Dam 1	NA
Saint Paul	NA
Grey Cloud Island	NA
Lock and Dam 2	NA
Lock and Dam 3	NA
Minnesota River	
Jordan	3.5
Fort Snelling	3.5
St. Croix River	
Stillwater	NA
Prescott	NA

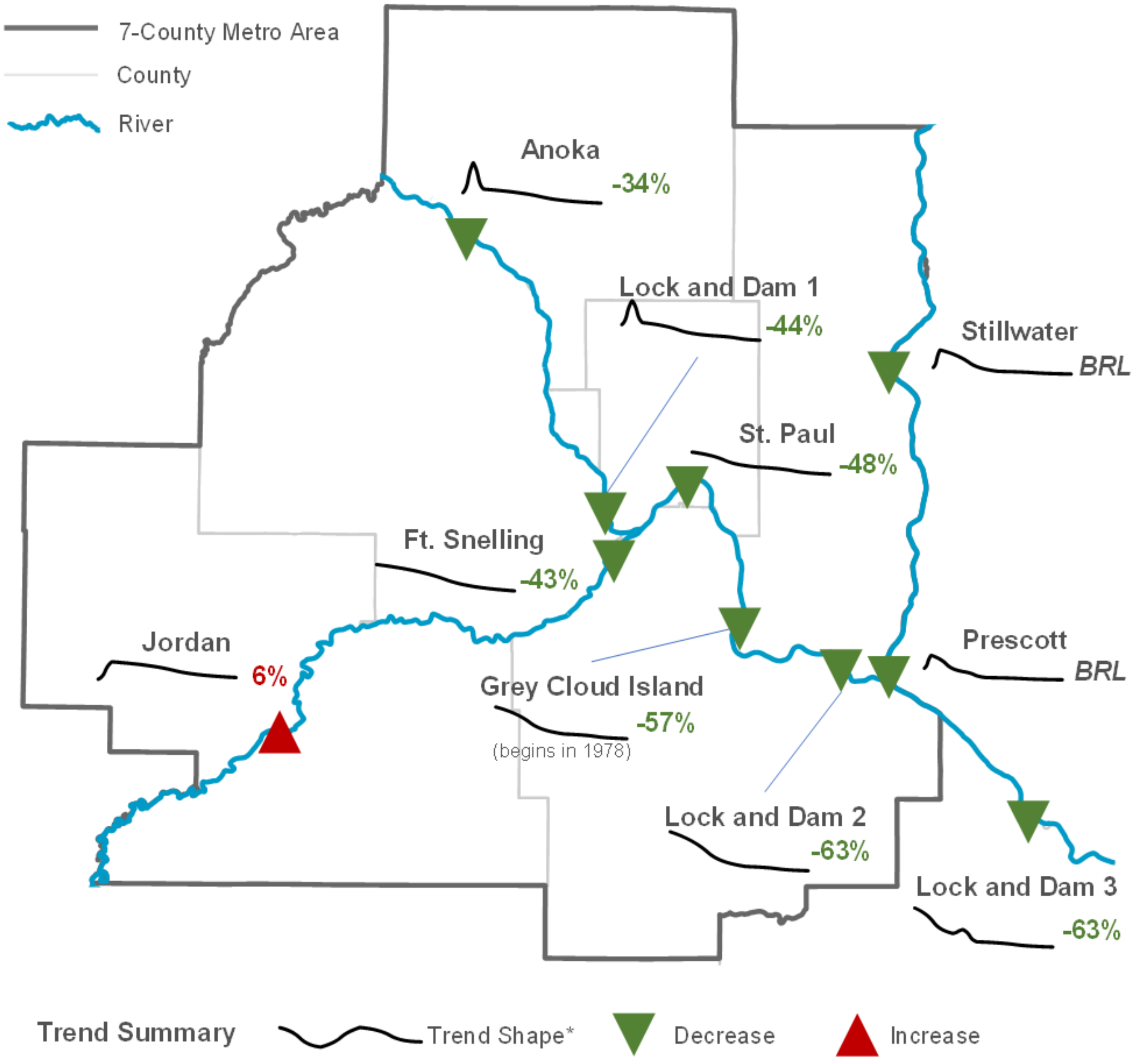
[a] Criteria are from Minnesota's river eutrophication standard. BOD_5 is one of the response criteria within the eutrophication standard. The values represent multi-year summer averages.

40-Year Trends. Figure 79 displays flow-adjusted BOD_5 concentration trends in the metro area rivers during the 1976-2015 assessment period. Trend results show that BOD_5 concentrations have decreased in the Mississippi River and the Minnesota River at Fort Snelling, indicating an improvement in water quality. While the BOD_5 concentrations estimated by QWTREND in the Minnesota River at Jordan have increased by 6% over the entire assessment period (1976-2015), a long-term decrease of 33% has been evident from 1990 to 2015 (see the detailed sub-trend analysis in the "Appendix"). No BOD_5 trends could be reported for the two St. Croix River sites because more than 10% of the BOD_5 concentrations measured at each site were less than the analytical RL (1.0 mg/L). In this circumstance, QWTREND results can only be used for exploratory analysis to understand trend directions. As such, the modeled trends showed decreases in BOD_5 concentrations at Stillwater and Prescott.

BOD_5 concentrations have consistently decreased along the Mississippi River, ranging from -34% at Anoka to -63% at Lock and Dam 3. A 43% decrease in BOD_5 concentration occurred in the Minnesota River at Fort Snelling. These decreasing trends are likely a reflection in part of significant MCES investments to reduce pollutant concentrations and loads in the discharges from its seven WWTPs that discharge to metro area rivers. For instance, major improvements in wastewater treatment technology at the Metro WWTP have resulted in substantial decreases in total BOD_5 concentrations discharged to the Mississippi River since the advent of secondary treatment in 1966 (Figure 80). Since implementation of advanced secondary treatment in 1984, BOD_5 discharge concentrations have been very low, averaging 2-3 mg/L since 2005. The Metro WWTP is the largest wastewater treatment facility in Minnesota, currently treating an average of 170 million gallons of wastewater per day.

Substantial reductions in BOD_5 concentrations at the Metro WWTP are likely responsible for the greater decreases in BOD_5 concentrations at Mississippi River sites downstream of the Metro WWTP (Grey Cloud Island, Lock and Dam 2, and Lock and Dam 3). Similarly, a 10-year project (1985-1995) to separate combined sewers in Minneapolis and Saint Paul likely contributed to the greater decreases in BOD_5 concentrations at Mississippi River sites near these cities (Lock and Dam 1 and Saint Paul). Decommissioning of the MCES Anoka WWTP in 1992 may also have contributed to the greater decrease in the BOD_5 concentration observed at Lock and Dam 1. Since 1970, comparable reductions in BOD_5 concentrations have occurred at six other MCES WWTPs. For example, substantial reductions in BOD_5 concentrations at the Blue Lake and Seneca WWTPs and decommissioning of the MCES Chaska WWTP (2000) likely contributed to a greater decrease in the flow-adjusted BOD_5 concentration at Fort Snelling. Similar improvements in WWTP technology state-wide have likely contributed to the decreasing trends in BOD_5 concentrations observed at the Mississippi, Minnesota, and St. Croix River entry points to the metro area.

Figure 79. Flow-Adjusted BOD_5 Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers, 1976-2015

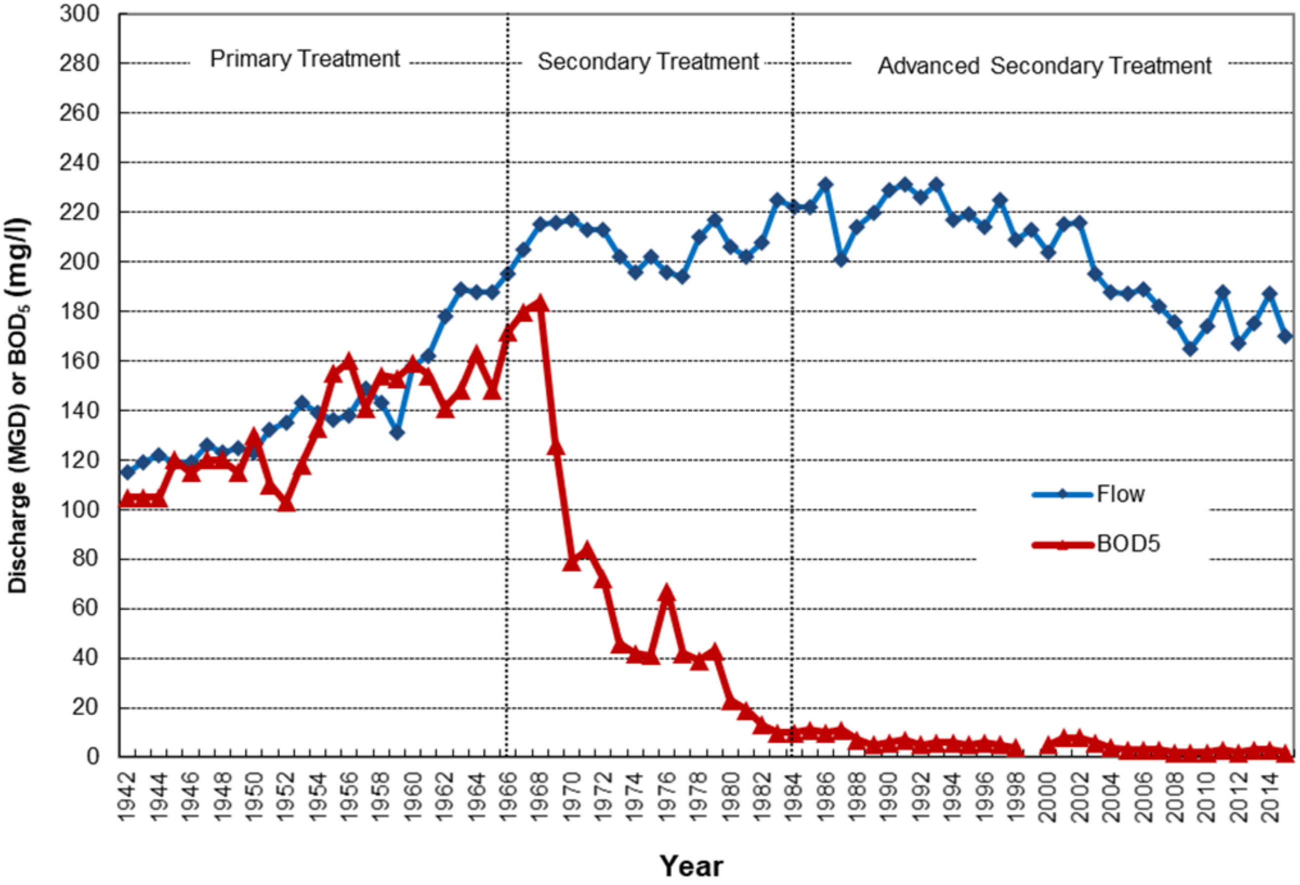


Presented with overall percentage change, unless noted with the following:

BRL – Below Reporting Limit
More than 10% of data are below the reporting limit, so a representative percentage could not be calculated

* Different scaling is applied to the lines of each site to visually emphasize the trend shapes. For accurate magnitudes of the trends, refer to the Results section of the report.

Figure 80. Annual Mean Metro Wastewater Treatment Plant Flow and BOD_5 Concentrations, 1942-2015



On average, BOD_5 concentrations have decreased by 51% in the Mississippi River and 19% in the Minnesota River during the 1976-2015 assessment period, while concentrations in the St. Croix River also exhibit a decreasing trend. Decreases in BOD_5 concentrations across the three regional rivers have also been recognized in a previous study by MCES (2004) (Table 25), which noted decreasing trends for BOD_5 concentrations in the Mississippi River at Anoka and Lock and Dam 3, the Minnesota River at Jordan, and the St. Croix River at Stillwater. These reductions in BOD_5 concentrations are an integrated result of MCES efforts to improve regional wastewater treatment, as well as implementation of regional and basin-wide pollution control programs. Continuing long-term monitoring and data analysis are needed to determine if these reductions in BOD_5 concentrations are sustainable.

Table 25. Results from Past Studies of BOD_5 Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers

Author	Study Period	Trend Analysis Method	Anoka	Lock and Dam 3	Jordan	Stillwater
MCES, 2004	1976-2002	SEAKEN	-52%	-59%	-38%	-58%

SEAKEN: nonparametric Seasonal Kendall test; locally-weighted scatterplot smoothing (LOWESS) procedure used to remove effects of flow on concentration

Temperature

Water temperature can have a substantial impact on water quality, because it can affect both the chemical and biological characteristics of a river. Organisms thrive within a preferred temperature range, with excursions outside of that range affecting rates of metabolism and photosynthesis and increasing susceptibility to stressors such as pollution, parasites, and diseases (USEPA, 2012c). Temperature influences water chemistry by affecting rates of chemical reactions and solubility of materials in water (USEPA 2012c; USGS, 2016b). For example, some materials are more soluble at warmer temperatures, which can increase conductivity, whereas gases like DO are less soluble at higher temperatures.

Water temperature depends on many factors, such as climate, weather, amount of shading, and contributions from groundwater flow and tributaries (USEPA 2012c; USGS, 2016b). Altering the amount of shading and adding impoundments such as dams can change the typical temperature of a waterbody. Inputs of cooling water (water used to cool machinery and industrial processes) and urban runoff can also increase water temperature (USEPA 2012c; USGS, 2016b).

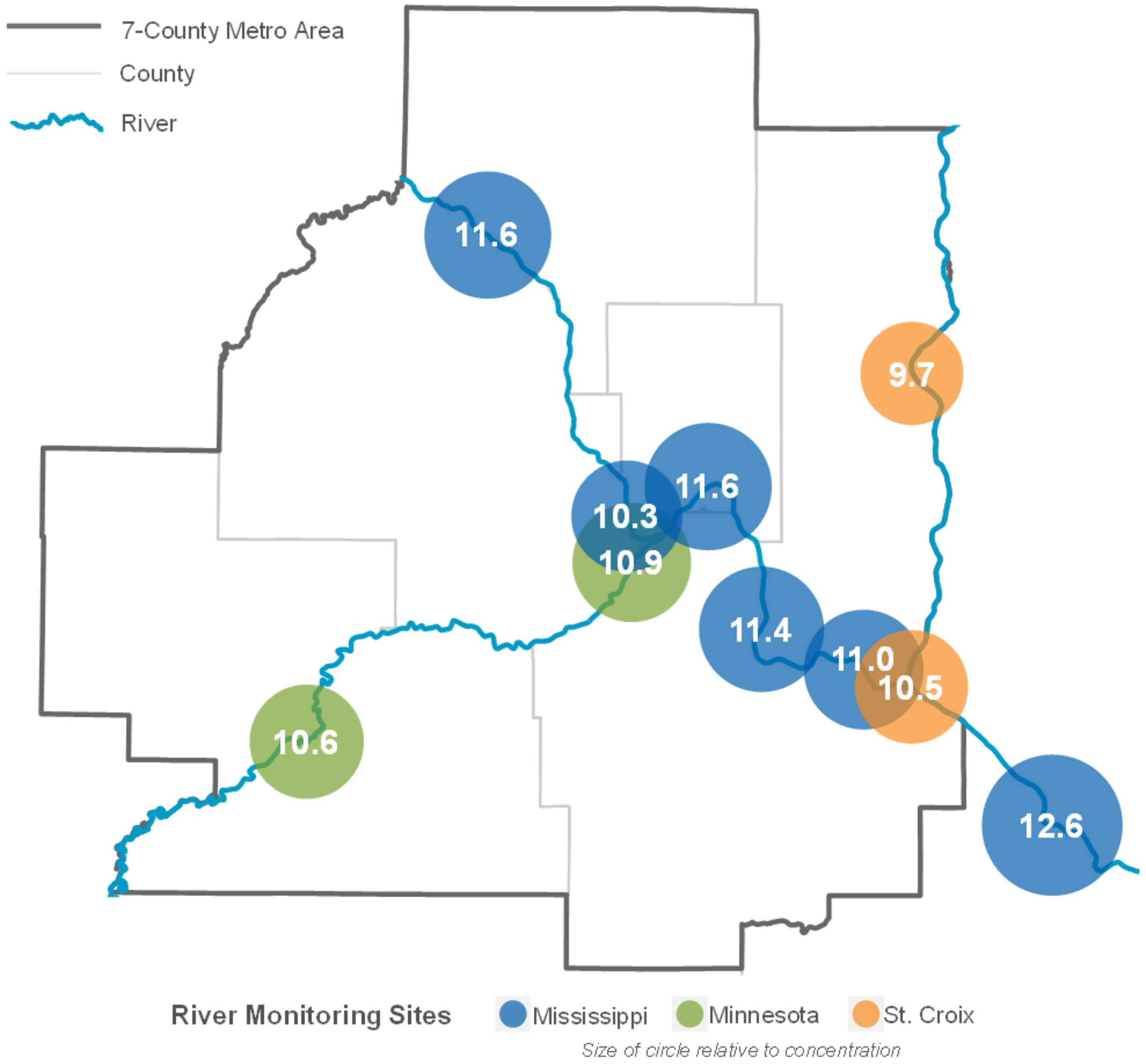
Recent Conditions. Figure 81 displays the median temperatures measured from 2006-2015 at river monitoring sites in the metro area. The data used to calculate these median temperatures were generally obtained in the morning, based on a set rotation of monitoring sites, so some sites were typically sampled earlier in the day than others. This is not an issue for most parameters, but it can create a bias in the results for parameters that have a strong diel cycle. On most days, water temperatures increase throughout the day and decrease at night. As a result, sites generally sampled later in the morning could have warmer temperatures than they would if sampled earlier in the morning. For this reason, care should be taken when interpreting any differences in the median temperatures between sites in Figure 81. A study using temperature measurements taken at comparable times of the day from each monitoring site would be needed to look at the differences between sites without the potential influence of varying sampling times.

There are many features of the metro area which may affect river temperatures. Regional rivers have locks and dams, significant inputs of urban runoff, and discharges from industries that utilize cooling water, all of which can impact water temperatures. Additionally, differences in river morphology and the amount of shading provided by riparian vegetation may affect river temperatures.

Minnesota has temperature standards for surface waters to protect the health of aquatic life. The standard limits the maximum allowable average daily temperature and restricts how much the monthly average of daily maximum temperatures deviates from natural levels (Minn. Rules Chapter 7050). There are currently no temperature impairments in the Mississippi, Minnesota, or St. Croix rivers within the metro area.

Trends. An evaluation of temperature trends at regional river monitoring sites is not included in this study. Lafrancois et. al (2013) noted an 8-13% increase in the temperature of the Mississippi River at Anoka, Lock and Dam 1, and Saint Paul; however, no trends were apparent at Grey Cloud Island and Lock and Dam 2. In contrast, a 9% decrease in the temperature of the Minnesota River at Fort Snelling occurred over the same time period (1976-2005).

Figure 81. Median Temperature (ºC) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



pH

pH represents how acidic or basic water is, specifically measuring the balance of hydrogen and hydroxyl ions. The pH scale ranges from 0 to 14, with 7 being neutral (an equal balance of hydrogen and hydroxyl ions). A pH value lower than 7 is acidic (more hydrogen ions than hydroxyl ions) and a pH value higher that 7 is basic (more hydroxyl ions than hydrogen ions). The pH scale is logarithmic, meaning a shift of 1 pH value represents a 10-fold change in the acidity. For example, a pH of 5 is 10 times more acidic than a pH of 6 and 100 times more acidic than a pH of 7.

pH affects many chemical and biological factors in water (USEPA, 2012d). Generally, most aquatic life thrives in a pH range of 6.5-9.0 (Freshwater Society, 2004). Biological functions of organisms, such as reproduction and respiration, can be hindered if the pH is outside of that range (Freshwater Society, 2004). pH can also affect the toxicity of some components in the water. For example, trace metals are more soluble at low pH values and are therefore more likely to impact aquatic life (USGS, 2016c). At high pH values, ammonium nitrogen is converted into un-ionized ammonia, a more toxic form (MPCA, 2013). pH can also affect the bioavailability of phosphorus (USGS, 2016c).

There are many natural and human-influenced factors that affect pH levels. The geology of the watershed can affect pH. For example, weathering of limestone gives water a “buffering capacity”, which is the ability to resist changes in pH to a certain degree (USU Extension, 2017). Decomposition of pine needles and leaves increases acidity, and photosynthesis and respiration of algae and aquatic organisms can cause shifts in pH as well (USU Extension, 2017). Rain is naturally acidic, with a pH around 5.6, but pollution from human activity (such as “acid rain”) can cause precipitation to have an even lower pH (Freshwater Society, 2004). Other human sources of acidic pollution include certain wastewater discharges and mine drainage (USU Extension, 2017).

Recent Conditions. Figure 82 displays the median pH values measured from 2006-2015 at river monitoring sites in the metro area. As with DO and temperature, some care must be taken when comparing slight differences in the median pH values. pH sometimes has a diel cycle fluctuation due to photosynthesis and respiration, and sampling dates and times vary between sites. Regardless, Figure 82 reflects some patterns across the metro region that are likely associated with differences between the three river watersheds.

Of the three metro area rivers, the St. Croix River had the lowest median pH values, while pH values in the Mississippi and Minnesota rivers were higher and very similar. The St. Croix River watershed is more forested (see “Study Area and Scope”), and decomposition of pine needles and leaves contributes to lower pH values (USU Extension, 2017). Sphagnum-dominated wetlands in the St. Croix River watershed are also sources of low pH drainage. Additionally, soils within the St. Croix River watershed have less capacity for buffering, and local waterbodies are more susceptible to pH changes from acidic sources (Freshwater Society, 2004).

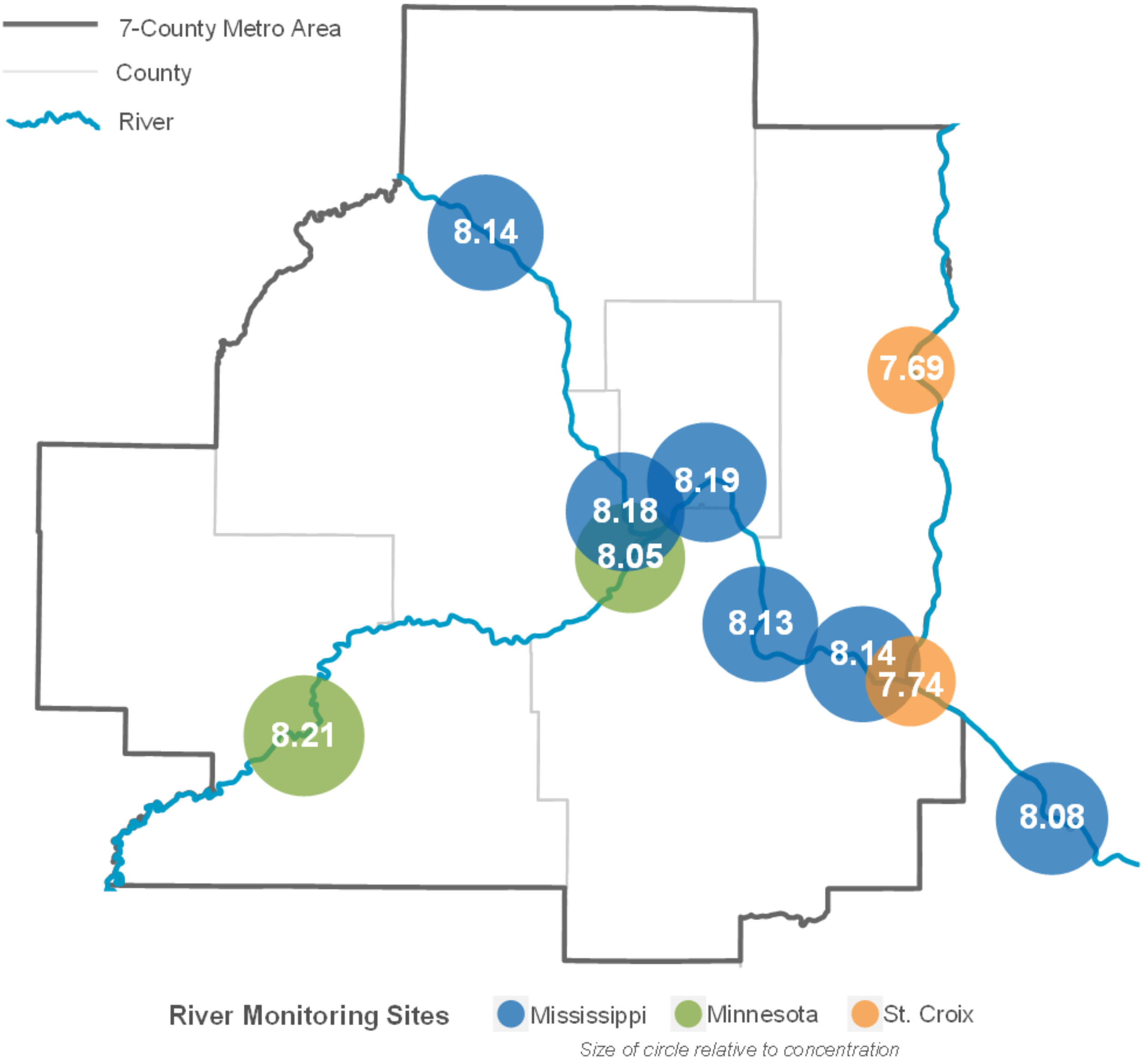
Median pH values changed slightly in all three rivers as they passed through the metro area. The largest change occurred in the Minnesota River, where the median pH value decreased from 8.21 at Jordan to 8.05 at Fort Snelling. Previous studies have suggested that conditions in the lower Minnesota River cause a net die-off of algae (MCES, 2010; MPCA, 2004a). Since algal decomposition typically reduces pH, this may be a mechanism that contributed to the lower pH at Fort Snelling. Although there were slight variations in pH values between sites, the median values were all within the range that supports aquatic life (6.5-9.0).

Minnesota has established a water quality standard for pH in surface waters, to protect the health of aquatic life. The standard requires that pH remains in a range from 6.5 to 9.0, except in the St. Croix

River, where the maximum pH value is 8.5 (Minn. Rules Chapter 7050). There are currently no pH impairments in the Mississippi, Minnesota, or St. Croix rivers within the metro area.

Trends. QWTREND was not used to investigate long-term trends in pH due to the limited range of variation of values. Lafrancois et al. (2013) noted a slight (2%) increase in pH in the Mississippi River at Grey Cloud Island (1976-2005). However, no significant trends were found at the other Mississippi and Minnesota River sites included in that study.

Figure 82. Median pH in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



Conductivity

Conductivity measures the ability of water to pass an electrical current, and it is affected by the concentration of ions in water, including Cl, NO_3, sulfate, phosphate, sodium, magnesium, calcium, iron, and aluminum (USEPA, 2012e). Due to their non-conductance, organic compounds such as oils decrease conductivity (USEPA, 2012e). Temperature also affects conductivity, so a correction is generally applied to report conductivity at 25 °C (referred to as “specific conductance”). All conductivity values used in this report have been corrected to 25 °C. Monitoring conductivity is informative because a notable change in conductivity can indicate a pollution source entering the river. For example, a failing septic system would increase the conductivity by contributing ions such as Cl, phosphate, and NO_3, while an oil spill would reduce the conductivity (USEPA, 2012e).

Conductivity is influenced by the geology through which rivers flow. For example, water that flows through an area with granite tends to have a lower conductivity than water that flows through an area with clay soil, since clay soil tends to have a much higher rate of weathering than granite (USEPA, 2012e).

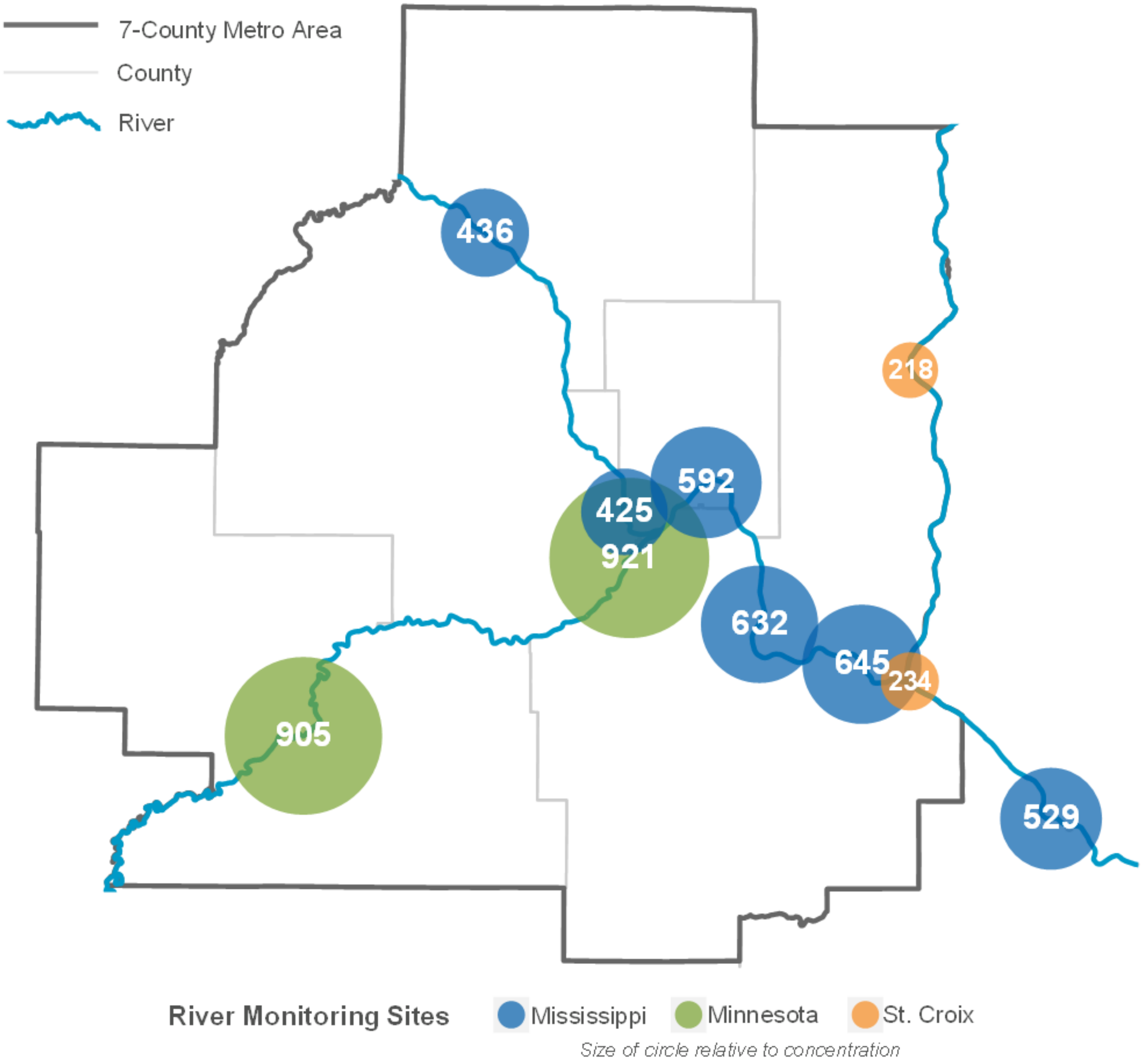
Recent Conditions. Figure 83 displays the median conductivity values measured from 2006-2015 at river monitoring sites in the metro area. As the three major rivers entered the metro area, the 10-year median conductivity value in the Minnesota River (905 umhos/cm at Jordan) was substantially higher than the 10-year median conductivity values at the entry points of the Mississippi River (436 umhos/cm at Anoka) and the St. Croix River (218 umhos/cm at Stillwater). This pattern is likely due to differences in the geology of these three watersheds, which is generally the main factor affecting conductivity (USEPA, 2012e). The Minnesota River watershed has a younger geology, with an abundance of glacial deposits that are susceptible to erosion (MPCA, 2009a; 2009c). Higher rates of erosion increase the opportunity for dissolved materials to enter the water, adding more ions and increasing the conductivity. The results of this study show that the Minnesota River had higher concentrations of NO_3 (Figure 95) and Cl (Figure 103), both ions that contribute to higher conductivity values.

In the metro area of the Mississippi River, median conductivity values were lowest in the upstream portion of the river, decreasing slightly between Anoka (436 umhos/cm) and Lock and Dam 1 (425 umhos/cm). The high conductivity in the Minnesota River (921 umhos/cm at Fort Snelling) caused the conductivity in the Mississippi River to increase between Lock and Dam 1 (425 umhos/cm) and Saint Paul (592 umhos/cm). The influence of higher conductivity in the Metro WWTP discharge likely resulted in the higher conductivity values observed at Grey Cloud Island (632 umhos/cm) and Lock and Dam 2 (645 umhos/cm). The low conductivity in the St. Croix River (234 umhos/cm at Prescott) provided a dilution effect in the Mississippi River, causing conductivity to decrease between Lock and Dam 2 (645 umhos/cm) and Lock and Dam 3 (529 umhos/cm).

In both the Minnesota and the St. Croix rivers, the median conductivity values increased slightly between upstream and downstream sites. Increases in conductivity values within these two river reaches and the Mississippi River reach from Saint Paul to Lock and Dam 2 may reflect urban sources of pollution such as stormwater. Median concentrations of both NO_3 (Figure 95) and Cl (Figure 103) also increased slightly in metro area river reaches, with potential sources noted later in their respective sections. Other ions not included in this report also likely contributed to the observed changes in conductivity.

Trends. QWTREND was not used to investigate long-term trends in conductivity. Lafrancois et al. (2013) noted increasing conductivity trends in the Mississippi River, ranging from 8-13% (1976-2005). However, no significant trend was found in the Minnesota River at Fort Snelling.

Figure 83. Median Conductivity (umhos/cm) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



Total Suspended Solids (TSS)

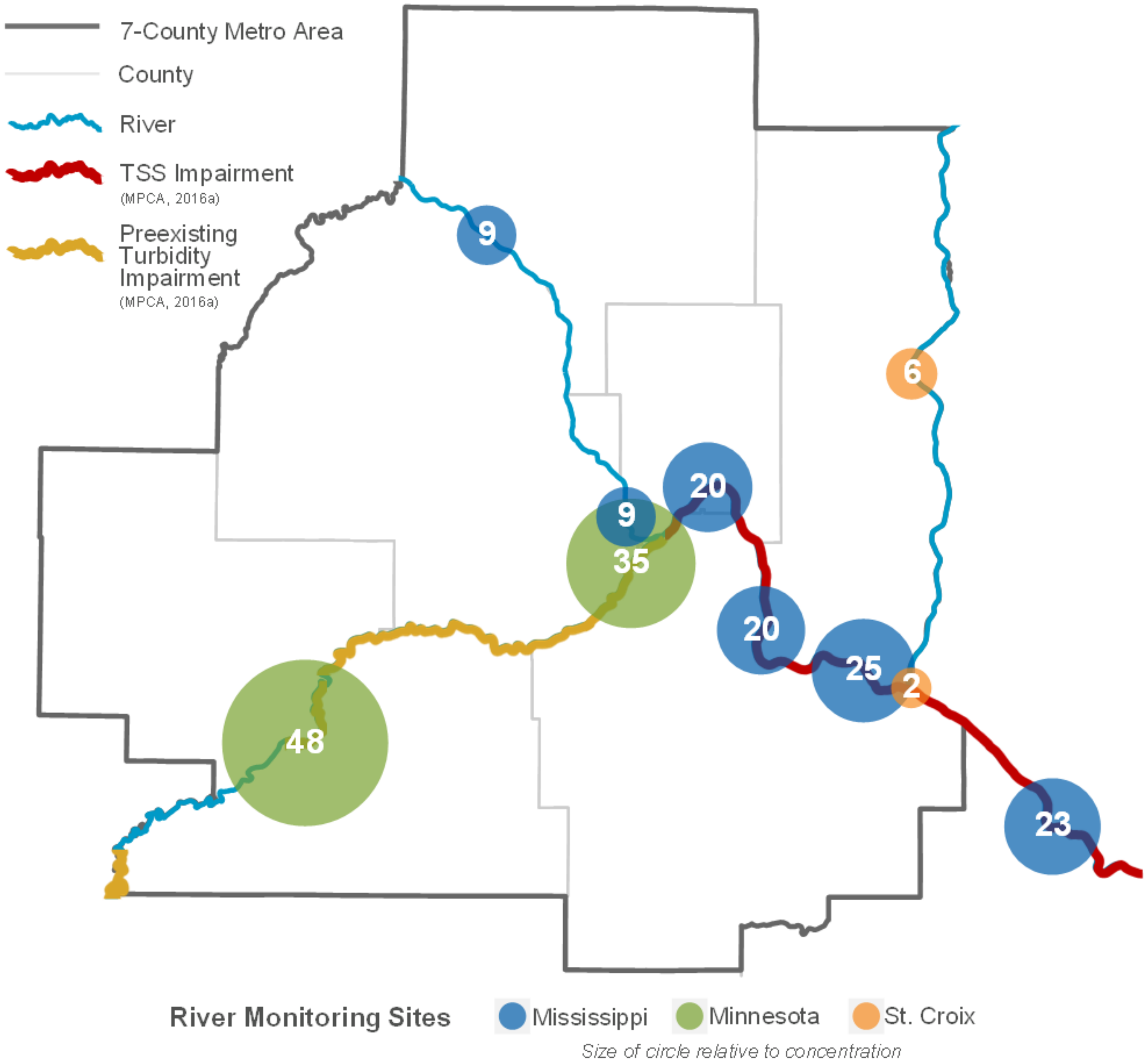
TSS are organic and inorganic particles suspended in water, including sediment (sand, silt, and clay particles), algae, plant material, and other fine organic matter (MPCA, 2011; USEPA, 2012f). Although sediment transport and sedimentation are naturally occurring processes in rivers, excessively high TSS concentrations can cause detrimental effects on river ecosystems by limiting light availability for plant growth, affecting the health of organisms, and degrading aquatic habitat (MPCA, 2015e; USEPA, 2012f). Additionally, other pollutants like phosphorus and trace metals can adhere to TSS particles and be carried downstream (USEPA, 2012f). Sources of high TSS include streambank erosion, algae growth, and watershed contributions, which depend on many factors such as soil type, slope, land cover, and human activities like excavation and agriculture (MPCA, 2015e). Excess sediment settles in the slow-moving upper Mississippi River navigation pools, and is also rapidly filling Lake Pepin, a natural lake on the Mississippi River 50 miles downstream of the Twin Cities (Engstrom and Almendinger, 2000).

Recent Conditions. Figure 84 displays the median TSS concentrations measured from 2006-2015 at each of the river monitoring sites in the metro area. As the three major rivers entered the metro area, the 10-year median TSS concentration in the Minnesota River (48 mg/L at Jordan) was substantially higher than the 10-year median TSS concentrations at the entry points of the Mississippi River (9 mg/L at Anoka) and the St. Croix River (6 mg/L at Stillwater). As noted in “Study Area and Scope,” the Minnesota River watershed has a different geological history and a higher percentage of agricultural land use than the Mississippi and St. Croix river watersheds. These geologic and land use factors make the Minnesota River watershed prime for erosion activity (MPCA, 2009a; 2009c). The flow-weighted median annual TSS concentrations in metro area tributaries also showed this contrast, with Minnesota River tributaries exhibiting higher TSS concentrations than those in Mississippi and St. Croix River tributaries (MCES, 2014). Most of the sediment in the Minnesota River watershed comes from eroding fields, ravines, gullies, and streambanks (MPCA, 2009c).

In the metro area stretch of the Mississippi River, median TSS concentrations were lowest in the upstream portion of the river (Anoka and Lock and Dam 1). The high TSS concentration in the Minnesota River (35 mg/L at Fort Snelling) caused the TSS concentration to double in the Mississippi River between Lock and Dam 1 (9 mg/L) and Saint Paul (20 mg/L). This Minnesota River impact influenced the entirety of Pool 2 in the Mississippi River, with the highest TSS concentration at Lock and Dam 2 (25 mg/L) also reflecting sediment resuspension and algal productivity (MPCA, 2015e). The very low TSS concentration in the St. Croix River (2 mg/L at Prescott) provided a dilution effect in the Mississippi River, causing TSS to slightly decrease between Lock and Dam 2 (25 mg/L) and Lock and Dam 3 (23 mg/L).

The pattern of 10-year median TSS concentrations in the three metro area rivers was very similar to that in a recent study (MPCA, 2015e) that estimated the origin of TSS loading to the South Metro Mississippi River. This study estimates that, during the 1985 to 2006 period, 74% of the TSS load came from the Minnesota River watershed, 16% came from the Upper Mississippi River watershed, and 3% came from the St. Croix River watershed, with the remainder contributed by smaller metro area tributaries and sources.

Figure 84. Median Total Suspended Solids Concentrations (mg/L) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



In both the metro Minnesota and St. Croix rivers, median TSS concentrations decreased between upstream and downstream sites. Sediment settles out in the lower channel of the Minnesota River between Jordan and Fort Snelling, due to slowly moving water caused by the navigation channel and backwater effects from Lock and Dam 2 on the Mississippi River (MPCA, 1985). River gauging records also show that the middle and lower Minnesota River are an overall sink for sediment (MPCA, 2009c). In the metro St. Croix River, a previous study (Lafrancois et al., 2009) found that TSS loads at the outlet of Lake St. Croix at Prescott were lower than the inlet loads at Stillwater. The slow-moving water of riverine lakes generally allows sedimentation, and this is likely the case in Lake St. Croix as well (MPCA, 2015e). In other words, more sediment is entering than leaving the metro Minnesota and St. Croix rivers, and TSS is settling out in depositional areas.

Total suspended solids passing through the metro area have a notable impact on downstream sections of the Mississippi River. Lake Pepin, located on the Mississippi River 12 miles downstream from Lock and Dam 3, has a problem with excess sedimentation and is filling in at a rate which is 10 times greater than it was 150 years ago (Engstrom and Almendinger, 2000; MPCA, 2015e). About 17% of the lake's volume in 1830 has been replaced by sediment, and at current accumulation rates, the remainder will be filled in another 340 years. It is estimated that 74-90% of the sediment delivered to Lake Pepin originates from the Minnesota River watershed (MPCA, 2009c; Kelly and Nater, 2000).

MCES WWTPs did not appear to influence the recent 10-year median TSS concentrations in metro area rivers. For example, the Mississippi River TSS concentration was 20 mg/L both above and below the Metro WWTP, at Saint Paul and Grey Cloud Island, respectively. In comparison to these Mississippi River TSS concentrations, the 10-year median TSS concentration in the Metro WWTP discharge was 2 mg/L, with the Metro WWTP median flow contributing only 3% of the median Mississippi River flow during the past 10-year period (MCES unpublished data accessed Dec. 2017). The 10-year median TSS concentrations decreased from upstream to downstream sites in the Minnesota and St. Croix rivers, despite the presence of MCES WWTPs along those river reaches. The 10-year median TSS concentrations in the Blue Lake and Seneca WWTP discharges were 2 mg/L and 3 mg/L, respectively, with these WWTPs combining to contribute only 2% of the median Minnesota River flow during the past 10-year period (MCES unpublished data accessed Dec. 2017). The St. Croix Valley median WWTP flow contributed far less than 1% of the St. Croix River's flow under most conditions, greatly limiting its impact on TSS concentrations in the river (MCES unpublished data accessed Dec. 2017).

TSS water quality standards for metro area rivers were established in 2014 by the MPCA, replacing the previous turbidity standard of 25 NTU. The TSS standard, allowable exceedance frequency, and applicable time period vary depending on the area or region of the state (Minn. Rules Chapter 7050).

The TSS standards at metro area river monitoring sites are shown in Table 26. Currently, the metro Minnesota River is listed as impaired by the MPCA for turbidity under the previous standard, and the metro Mississippi River below the Minnesota River confluence through upper Lake Pepin is listed as impaired for TSS under the new standard (MPCA, 2015e; 2016a). TSS sources contributing to the impaired reach of the metro Mississippi River include the Minnesota River (74%), the Upper Mississippi River (16%), and metro area urban runoff (4%) (MPCA, 2015e). Since the TSS standards only apply during the warmer months when TSS concentrations are higher, they are not directly comparable to the 10-year median TSS concentrations presented in Figure 84, which include year-round data. Hence, no comparisons are made in this report.

40-Year Trends. Figure 85 displays flow-adjusted TSS concentration trends in the metro area rivers. Trend results show that TSS concentrations have significantly decreased across all three rivers during the last 40 years, indicating an improvement in water quality. Substantial reductions in TSS concentrations occurred at river entry points to the metro area, including a 56% reduction in the Mississippi River at Anoka, a 37% reduction in the Minnesota River at Jordan, and a 48% reduction in the St. Croix River at Stillwater. MCES (2004) also used MCES monitoring data to evaluate TSS concentration trends at river entry points to the metro area during the 1976-2002 period, finding a 45% reduction in the Mississippi River at Anoka and a 43% reduction in the St. Croix River at Stillwater. Due to the nature of the statistical test used, it was not possible to determine whether a trend occurred in the Minnesota River at Jordan.

Table 26. Total Suspended Solids Standards at Metro Monitoring Sites

Site	TSS Standard (mg/L)	Applicable Date Range
Mississippi River		
Anoka	30	Apr - Sept
Lock and Dam 1	30	Apr - Sept
Saint Paul	32	June - Sept
Grey Cloud Island	32	June - Sept
Lock and Dam 2	32	June - Sept
Lock and Dam 3	32	June - Sept
Minnesota River		
Jordan	65	Apr - Sept
Fort Snelling	65	Apr - Sept
St. Croix River		
Stillwater	15	Apr - Sept
Prescott	15	Apr – Sept

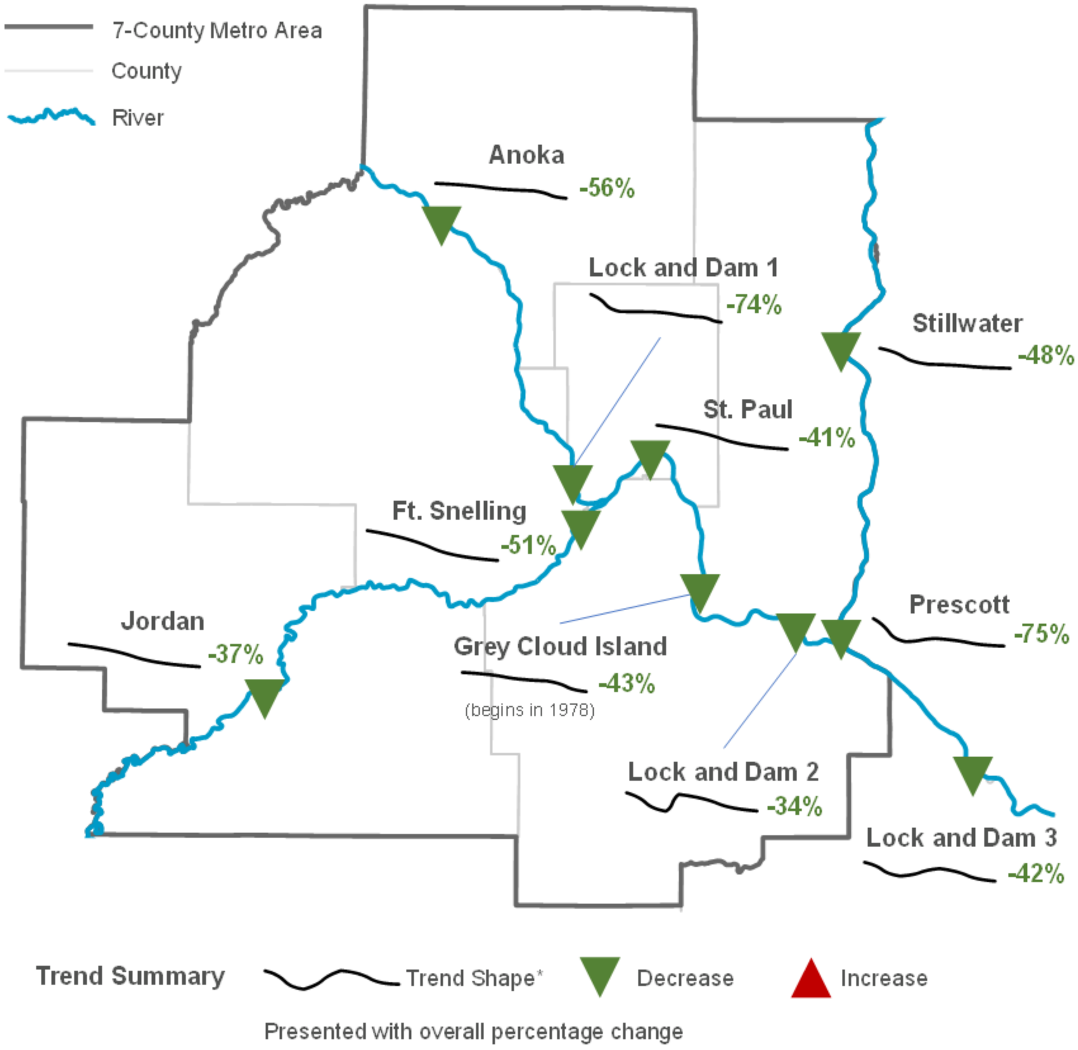
Downstream from the Mississippi River entry point at Anoka, the greatest decrease in TSS concentration (74%) occurred at Lock and Dam 1, likely due in part to sediment trapping in Pool 1 (above Lock and Dam 1) and TSS reductions associated with an extensive combined sewer overflow separation project that was implemented by the cities of Minneapolis and Saint Paul during the 1985-1995 period. Due to high TSS contributions from the Minnesota River, decreases in TSS concentrations were more moderate at Mississippi River sites downstream from the Minnesota River confluence, ranging from 34% to 43%. Using a different statistical method to assess metro area Mississippi River TSS trends during the 1976-2005 period, Lafrancois et al. (2013) noted similar reductions in TSS concentrations (Table 27) through the Mississippi National River and Recreation Area, at the same monitoring sites used in this report. These reductions ranged from 20%-40%, although no TSS concentration trend was apparent at Lock and Dam 2.

MCES (2004) noted no significant trend in TSS concentrations at Lock and Dam 3 during the 1976-2002 period. With more than 10 years of additional data, the current MCES trend analysis now shows significant reductions in TSS concentrations at both Lock and Dam 2 (34%) and Lock and Dam 3 (42%). In addition, Weller and Russell (2016) noted that summer TSS concentrations at Lock and Dam 2 have decreased by 23% during the 1976-2014 period.

In the Minnesota River, the greater decrease in TSS concentration (51%) occurred at the downstream Fort Snelling site, although a significant decrease (37%) was also apparent at Jordan. Using MCES data, MPCA (2002) found a 40% reduction in TSS concentrations at Fort Snelling during the 1976-2001 period and a 31% reduction in TSS concentrations at Jordan during the 1977-2001 period. Johnson (2009) noted a 35% reduction in TSS concentrations at Fort Snelling during the 1976-2003 period, while Lafrancois et al. (2013) reported a 62% decrease in TSS concentrations at Fort Snelling during the 1976-2005 period (Table 27).

In part, the greater decreases in TSS concentrations at Fort Snelling may reflect sediment trapping and deposition in the lower Minnesota River channel, especially during periods of lower flow. The Lower Minnesota River and a number of its metro area tributaries (Bevens, Bluff, Carver, Riley, and Sand Creeks and Credit River) are among those watersheds in the South Metro Mississippi River Basin with the highest TSS concentrations (MPCA, 2015e; MCES, 2014). All of these metro area tributaries have been listed by the MPCA as impaired for aquatic life due to excess levels of turbidity (the water quality standard is now based on TSS). As a result, the MPCA has worked with local water resources management organizations in the metro area to develop and implement TMDL plans that will reduce TSS concentrations and loads to the Lower Minnesota River. Many TSS-related TMDL projects have been successfully implemented during recent years. For example, efforts to reduce TSS concentrations and loads in the Credit River Watershed have led to de-listing in 2011 of the turbidity impairment identified in 2002 (SCWD, 2012).

Figure 85. Flow-Adjusted Total Suspended Solids Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers, 1976-2015



* Different scaling is applied to the lines of each site to visually emphasize the trend shapes. For accurate magnitudes of the trends, refer to the Results section of the report.

Table 27. Results from Past Studies on Total Suspended Solids Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers

Author	Study Period	Trend Analysis Method	Anoka	Lock and Dam 1	Saint Paul	Grey Cloud Island	Lock and Dam 2	Jordan	Fort Snelling	Stillwater
MPCA, 2002	1976-2001	SEAKEN						-31%	-40%	
MCES, 2004	1976-2002	SEAKEN	-45%					NM		-43%
Johnson, 2009	1976-2003	QWTREND							-35%	
Lafrancois, 2013	1976-2005	SEAKEN	-20%	-40%	-32%	-26%	NT		-62%	

SEAKEN: nonparametric Seasonal Kendall test; locally-weighted scatterplot smoothing (LOWESS) procedure used to remove effects of flow on concentration

NM: non-monotonic trend

NT: no significant trend

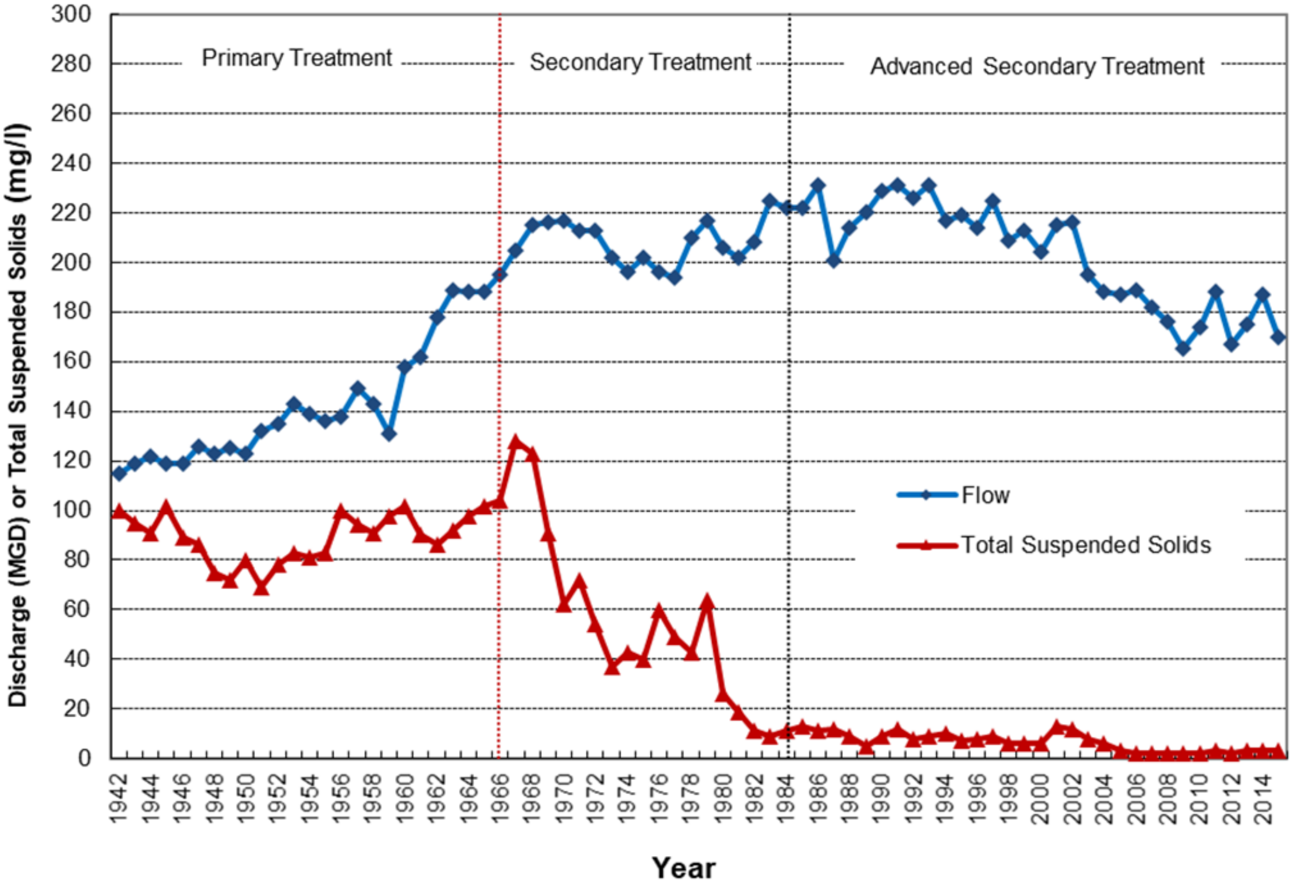
A long-term trend analysis of MCES water quality data for the Credit River indicates a 63% reduction in TSS concentration (MCES, 2014). Similar long-term and short-term (2008-2012) reductions in TSS concentrations have been noted at Bevens Creek (39% and 6%), Bluff Creek (76% and 19%), Carver Creek (56% and 10%), and Riley Creek (65% and 47%). Nine Mile Creek was previously listed as impaired for turbidity, but was delisted in 2010, likely due to decreasing sediment concentrations (90% long-term and 16% short-term) resulting from numerous stream improvement projects completed by the Nine Mile Creek Watershed District (MCES, 2014). All of these successful efforts to reduce TSS concentrations and loads in metro area tributaries of the Lower Minnesota River have likely contributed to the TSS concentration reduction (51%) at Fort Snelling.

In the St. Croix River, the greater decrease in TSS concentration (75%) occurred at the downstream Prescott site, although a significant decrease (48%) was also apparent upstream at Stillwater. In large part, the greater decrease at Prescott reflects sediment trapping and deposition in the 23-mile length of Lake St. Croix. Lafrancois et al. (2009) also noted significant TSS concentration reductions at Stillwater and Prescott during the 1976-2004 period. Although the overall magnitudes of those TSS trends were not determined, rates of change in TSS concentrations were -0.06 mg/L/year and -0.03 mg/L/year at Stillwater and Prescott, respectively.

Long-term decreasing TSS trends across all three major rivers in the metro area are likely due in part to improved treatment at MCES WWTPs. Prior to implementation of secondary treatment in 1966, the Metro WWTP was a major contributor of TSS to the Mississippi River, with mean annual TSS concentrations ranging from 72-128 mg/L during the 1942-1966 period (Figure 86). With implementation of secondary wastewater treatment technology in 1966 and advanced secondary treatment technology in 1984, mean annual TSS concentrations decreased from 128 mg/L to 3 mg/L (98%) during the 1966-2015 period and from 60 mg/L to 3 mg/L (95%) during the 1976-2015 period. The benefits of reduced TSS concentrations at the Metro WWTP are likely reflected by the greater reduction in TSS concentrations at Grey Cloud Island (43%), compared to the reduction at Saint Paul (41%), upstream from the Metro WWTP discharge. Similar wastewater treatment technology has been implemented at the MCES WWTPs (Blue Lake and Seneca) discharging to the Minnesota River, which may have contributed in part to a greater reduction in TSS concentration at Fort Snelling (51%), compared to that at Jordan (37%).

On average, TSS concentrations decreased by 48%, 44% and 62%, respectively, in the Mississippi River, Minnesota River and St. Croix River within the metro area. The decreasing TSS concentrations noted in this report are consistent with TSS trend results reported by other authors (Johnson, 2009; Lafrancois et al., 2009; Lafrancois et al., 2013; MCES, 2004; MPCA, 2002; Weller and Russell, 2016). MPCA (2015e) notes that MCES WWTPs and metro area runoff are minor sources of the sediment load to the metro Mississippi River under average flow conditions, contributing 2% and 4%, respectively. In contrast, 76% of the sediment load flowing into the metro Mississippi River comes from the highly agricultural Minnesota River basin, where eroding river bluffs, ravines, stream banks and farm fields are the primary sources of sediment. Successful efforts to reduce TSS concentrations and loads in metro area tributaries and at MCES WWTPs have likely provided relatively minor contributions to the decreasing TSS trends noted in the three rivers. Given the magnitude of the TSS trends observed and the dominant influence of the Minnesota River on TSS concentrations at most metro area monitoring sites, it is possible that improvements in agricultural and land management practices (contour plowing, conservation tillage, Conservation Reserve Program, stream bank stabilization, riparian buffers) are also responsible for decreasing TSS concentrations (Lafrancois et al., 2013). Reduced TSS concentrations may also be due to natural river variation and reduced channel widening, suggesting that long-term sediment concentrations and loads may naturally decline once river channels accommodate increased flows and stop widening (Lenhart et al., 2012). Although TSS concentrations have significantly decreased in the metro area Mississippi, Minnesota, and St. Croix rivers, the lower Minnesota River and the Mississippi River reach from Lock and Dam 1 to upper Lake Pepin remain impaired, due to excessively high TSS concentrations. Continuing long-term monitoring and data analysis are needed to determine if current TSS reductions are sustainable and TMDL goals can be achieved for the impaired river reaches.

Figure 86. Annual Mean Metro Wastewater Treatment Plant Discharge Flow and Total Suspended Solids Concentrations, 1942-2015



Total Phosphorus (TP)

TP is a nutrient that exists naturally in rivers and is important for river health. However, excess TP can be harmful, leading to severe algae growth and low oxygen concentrations, which can cause uninhabitable conditions for most aquatic life, poor drinking water quality, unpleasant environments for recreation, and potential health impacts for people and pets (MPCA, 2004b). In Minnesota, the main contributors of TP to surface waters are agricultural runoff, atmospheric deposition, permitted wastewater discharges, and streambank erosion. Other TP sources include urban runoff (for example, pet and yard wastes), nonagricultural rural runoff, and septic systems (MPCA, 2014).

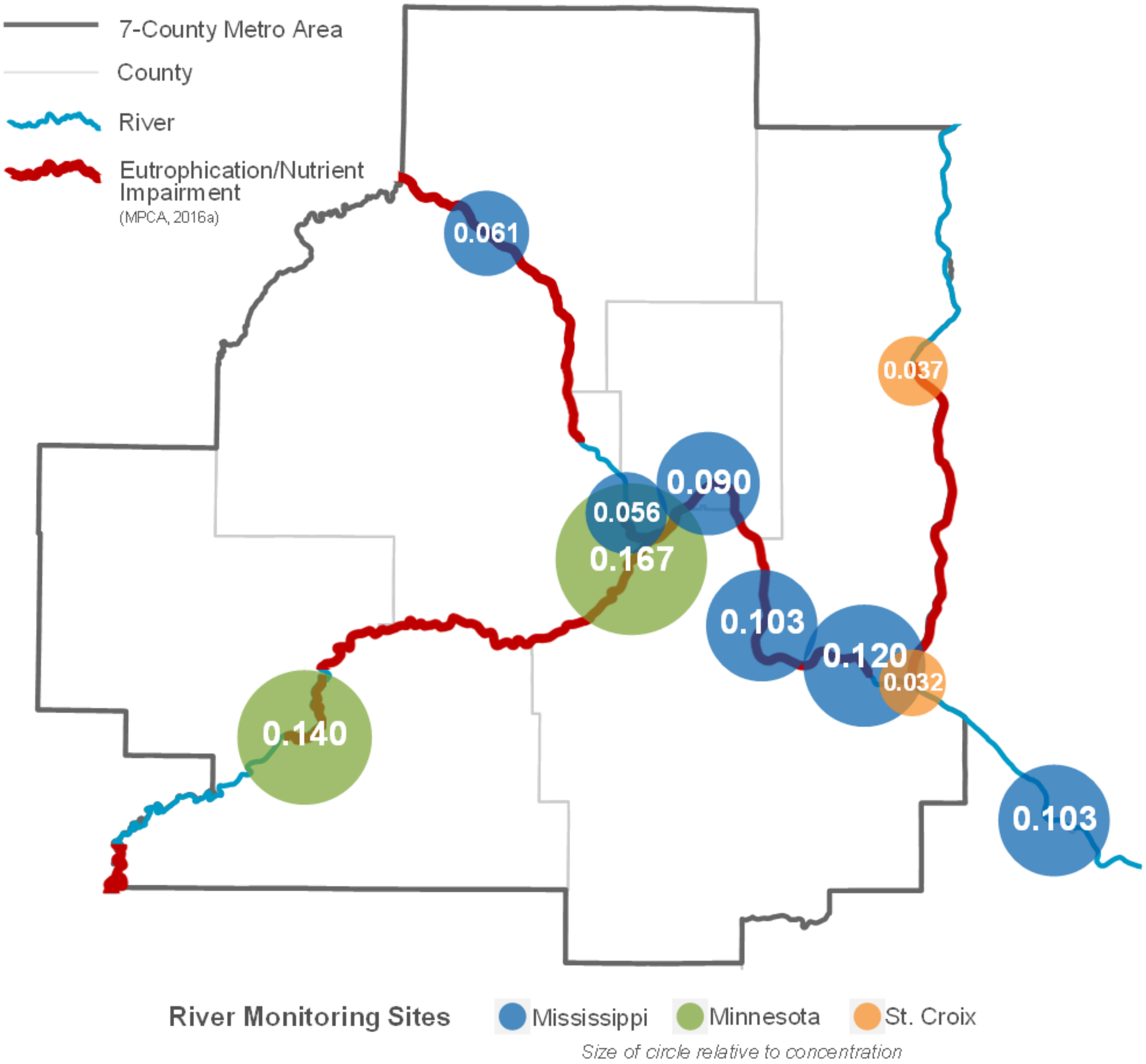
Recent Conditions. Figure 87 displays the median TP concentrations measured from 2006-2015 at each of the river monitoring sites in the metro area. As the three major rivers entered the metro area, the Minnesota River had the highest 10-year median TP concentration (0.140 mg/L at Jordan), the St. Croix River had the lowest concentration (0.039 mg/L at Stillwater), and the Mississippi River had an intermediate concentration (0.061 mg/L at Anoka). These differences in TP concentrations are primarily due to differences in land cover and land use within the three watersheds. Approximately 66% of the Minnesota River watershed is used for agriculture, while agricultural land use in the upper Mississippi and St. Croix river watersheds is only 23% and 20%, respectively (see “Study Area and Scope”). Statewide, the largest contributor of phosphorus to surface waters in average flow conditions is runoff from agricultural land (MPCA, 2004b; 2014).

Geological differences between the three watersheds also play a role in the differences in median TP concentrations at the river entry points. Streambank erosion is a significant source of excess TP, especially in wetter conditions (MPCA, 2014). As previously noted in the TSS discussion, the geology of the Minnesota River makes it susceptible to erosion (MPCA, 2009a; 2009c), and the Minnesota River also has the highest 10-year median TSS concentrations (Figure 84). With phosphorus readily adsorbing to total suspended solids, erosional sources in the Minnesota River watershed (fields, ravines, gullies, and streambanks) (MPCA, 2009c) likely facilitated higher TP concentrations in the Minnesota River.

The patterns of 10-year median TP concentrations in the three metro area rivers were consistent with patterns of TP concentrations in their tributaries. Flow-weighted median annual TP concentrations in Minnesota River tributaries (2003-2012) were generally higher than those in Mississippi and St. Croix river tributaries (MCES, 2014), as was also the case for TSS concentrations.

In the metro area of the Mississippi River, median TP concentrations were lowest in the upstream portion of the river (at Anoka and Lock and Dam 1). The high TP concentration in the Minnesota River (0.167 mg/L at Fort Snelling) caused the TP concentration in the Mississippi River to increase between Lock and Dam 1 (0.056 mg/L) and Saint Paul (0.090 mg/L). This Minnesota River impact influenced TP concentrations in the entirety of Pool 2 in the Mississippi River, although higher TP concentrations at Grey Cloud Island and Lock and Dam 2 also reflected the phosphorus contribution from the Metro WWTP. During the 2006-2015 period, the median TP concentration in the Metro WWTP discharge was 0.28 mg/L, with the Metro WWTP contributing 3% of the median Mississippi River flow (MCES unpublished data accessed Dec. 2017). The low TP concentration in the St. Croix River (0.032 mg/L at Prescott) provided a dilution effect in the Mississippi River, causing TP to slightly decrease between Lock and Dam 2 (0.120 mg/L) and Lock and Dam 3 (0.103 mg/L).

Figure 87. Median Total Phosphorus Concentrations (mg/L) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



The TP concentration increased in the Minnesota River as it passed through the metro area, with a 19% increase noted between Jordan and Fort Snelling. A portion of this increase in TP concentration was likely due to phosphorus contributions from the Blue Lake and Seneca WWTPs and Minnesota River tributaries. During the 2006-2015 period, the median TP concentrations in the Blue Lake and Seneca WWTP discharges were 0.41 mg/L and 0.51 mg/L, respectively, with both WWTPs combining to contribute 2% of the median Minnesota River flow (MCES unpublished data accessed Dec. 2017). In comparison, median annual flow-weighed mean concentrations of TP in Minnesota River tributaries ranged from 0.055-0.526 mg/L during the 2003-2012 period (MCES, 2014), with the highest concentrations present in those tributaries with predominantly agricultural land use in their watersheds.

In the St. Croix River, the TP concentration decreased by 14% between Stillwater and Prescott. This decrease was likely due to settling of TSS-associated phosphorus and algal uptake of phosphorus in Lake St. Croix.

Given the complexity of phosphorus dynamics in metro area rivers (James, 2007; James and Larson, 2008), it is difficult to identify all reasons for the differences in TP concentrations observed across the Mississippi, Minnesota, and St. Croix rivers. Phosphorus is contributed by a variety of point and nonpoint sources and exists in several forms in the river that are influenced by both biotic and abiotic factors, depending on river flow conditions (James and Larson, 2008; MCES, 2010; MPCA, 2004a; 2014).

TP in the rivers flowing through the metro area also impacts downstream water quality. In 2004, Lake Pepin was listed by the MPCA as impaired for excess nutrients, with the Twin Cities Metro Area and the Upper Mississippi, Minnesota, and St. Croix river watersheds identified as the four primary sources of phosphorus (MPCA, 2007). Additionally, nutrients (including phosphorus) are transported down the Mississippi River into the Gulf of Mexico, where they contribute to the hypoxic Dead Zone (Alexander et al., 2000; Rabalais et al., 2002). The section of the Mississippi River upstream from the Ohio River confluence contributes 26% of the total phosphorus load delivered by the river annually to the Gulf of Mexico (Alexander et al., 2008).

Table 28. Eutrophication Criteria at Metro Monitoring Sites – Total Phosphorus

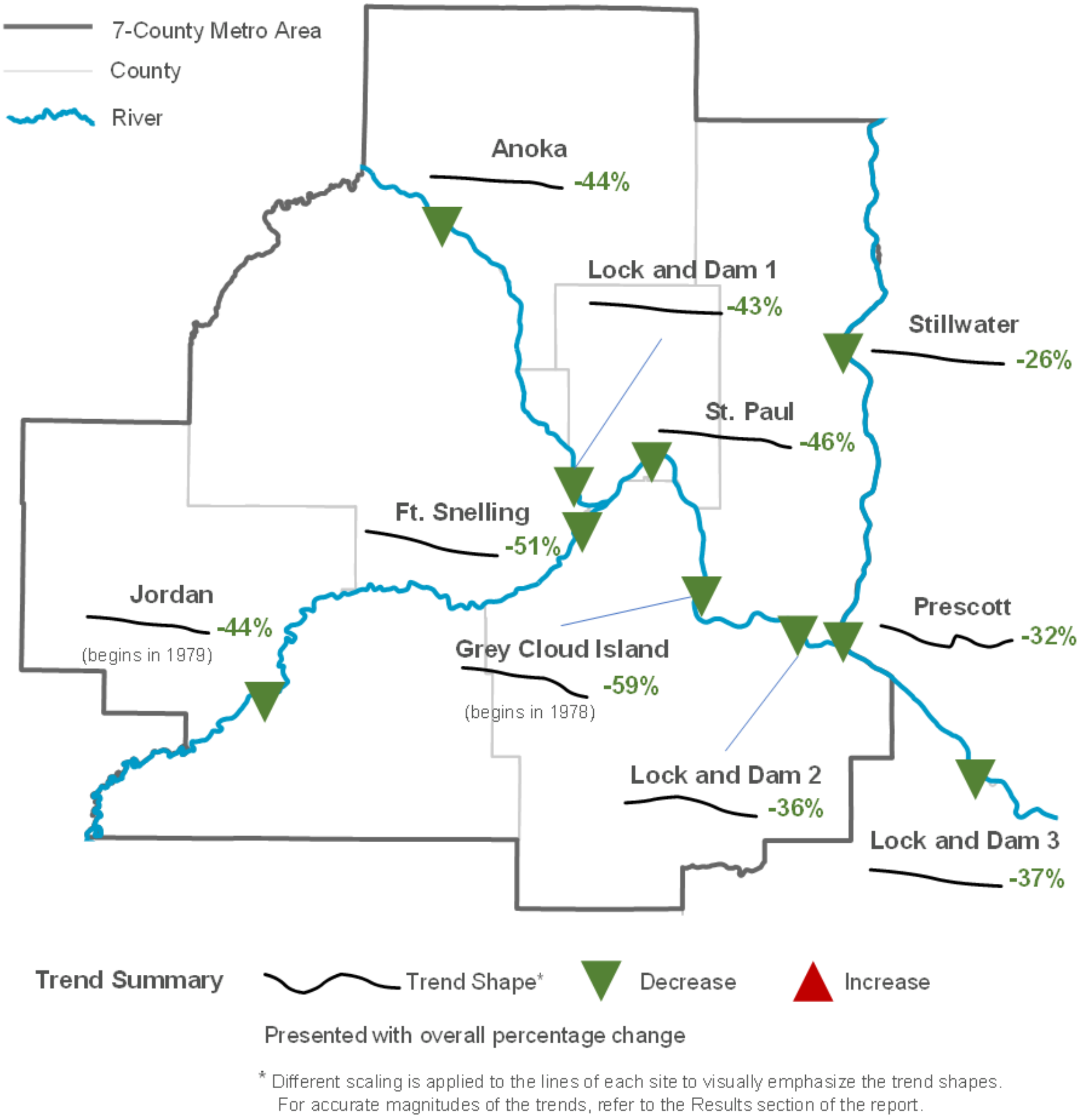
Site	TP Criteria (mg/L) [a]
Mississippi River	
Anoka	0.100
Lock and Dam 1	0.100
Saint Paul	0.125
Grey Cloud Island	0.125
Lock and Dam 2	0.125
Lock and Dam 3	0.100
Minnesota River	
Jordan	0.150
Fort Snelling	0.150
St. Croix River	
Stillwater	0.040
Prescott	0.040

[a] Criteria are from Minnesota's river and lake eutrophication standards. TP is the causative criteria within the eutrophication standards. The values represent multi-year summer averages.

The MPCA has established TP criteria as part of Minnesota's eutrophication standards (Minn. Rules Chapter 7050; MPCA, 2015d; Heiskary and Wilson, 2008). A river or lake eutrophication impairment exists if the criteria for the causative variable, TP, as well as the criteria for one or more response variables, are exceeded. The TP criteria at metro area river monitoring sites are listed in Table 28. The criteria for the St. Croix River sites are defined by the lake eutrophication standard instead of the river standard because they are located in Lake St. Croix. The TP criteria represent multi-year summer average concentrations, so they are not comparable to the 10-year median TP concentrations in Figure 87. Regardless, seven of the 10 river monitoring sites are on river reaches that have been listed by MPCA as impaired for eutrophication, as shown in Figure 87 (MPCA, 2012; 2016a).

40-Year Trends. Figure 88 displays overall trends in flow-adjusted TP concentrations in the metro area Mississippi, Minnesota, and St. Croix rivers. Trend results show that TP concentrations have significantly decreased across all three rivers during the last 40 years, indicating an improvement in water quality. Substantial reductions in TP concentrations occurred at river entry points to the metro area, including 44% reductions in the Mississippi River at Anoka and the Minnesota River at Jordan, and a 26% reduction in the St. Croix River at Stillwater. MCES (2004) previously evaluated TP concentration trends at river entry points to the metro area during the 1976-2002 period, finding a 37% reduction in the Mississippi River at Anoka (Table 29), but no reduction (no trend) in the St. Croix River at Stillwater. Due to the nature of the statistical test used, it was not possible to determine whether a trend occurred in the Minnesota River at Jordan.

Figure 88: Flow-Adjusted Total Phosphorus Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers, 1976-2015



* Different scaling is applied to the lines of each site to visually emphasize the trend shapes. For accurate magnitudes of the trends, refer to the Results section of the report.

Table 29. Results from Past Studies on Total Phosphorus Concentration Trends in the Mississippi and Minnesota Rivers

Author	Study Period	Trend Analysis Method	Anoka	Lock and Dam 1	Saint Paul	Grey Cloud Island	Lock and Dam 2	Lock and Dam 3	Jordan	Fort Snelling
MCES, 2004	1976-2002	SEAKEN	-37%*					-20%*	NM*	
Johnson, 2009	1976-2003	QWTREND								-52%
Lafrancois, 2013	1976-2005	SEAKEN	-15%	-27%	-29%	-37%	-28%			-71%

SEAKEN: nonparametric Seasonal Kendall test

NM: non-monotonic trend

* Locally-weighted scatterplot smoothing (LOWESS) procedure used to remove effects of flow on concentration

Downstream from the Mississippi River entry point at Anoka, the greatest decrease in TP concentration (59%) occurred at Grey Cloud Island, while decreases at other Mississippi River sites were more moderate, ranging from 36% (Lock and Dam 2) to 46% (Saint Paul). Using a different statistical method to assess metro area Mississippi River TP trends during the 1976-2005 period, Lafrancois et al. (2013) noted similar reductions in TP concentrations (Table 29) through the Mississippi National River and Recreation Area, at the same monitoring sites used in this report. These reductions ranged from 15% at Anoka to 37% at Grey Cloud Island. The 2016 State of the River Report, published by the Friends of the Mississippi River and the National Park Service (2016), noted that average summer TP concentrations at Lock and Dam 2 have decreased by 35% during the 1976-2014 period. MCES (2004) found a 20% reduction in TP concentrations at Lock and Dam 3 during the 1976-2002 period.

In the Minnesota River, a slightly greater decrease in TP concentration (51%) occurred at the downstream Fort Snelling site, compared to the upstream decrease (44%) at Jordan. Using MCES data, MPCA (2002) found a 35% reduction in TP concentrations at Fort Snelling during the 1976-2001 period; however, no trend in TP concentrations was evident at Jordan during the 1977-2001 period. Johnson (2009) and Lafrancois et al. (2013) noted TP concentration reductions of 52% and 71% at Fort Snelling during the 1976-2003 and 1976-2005 periods, respectively (Table 29).

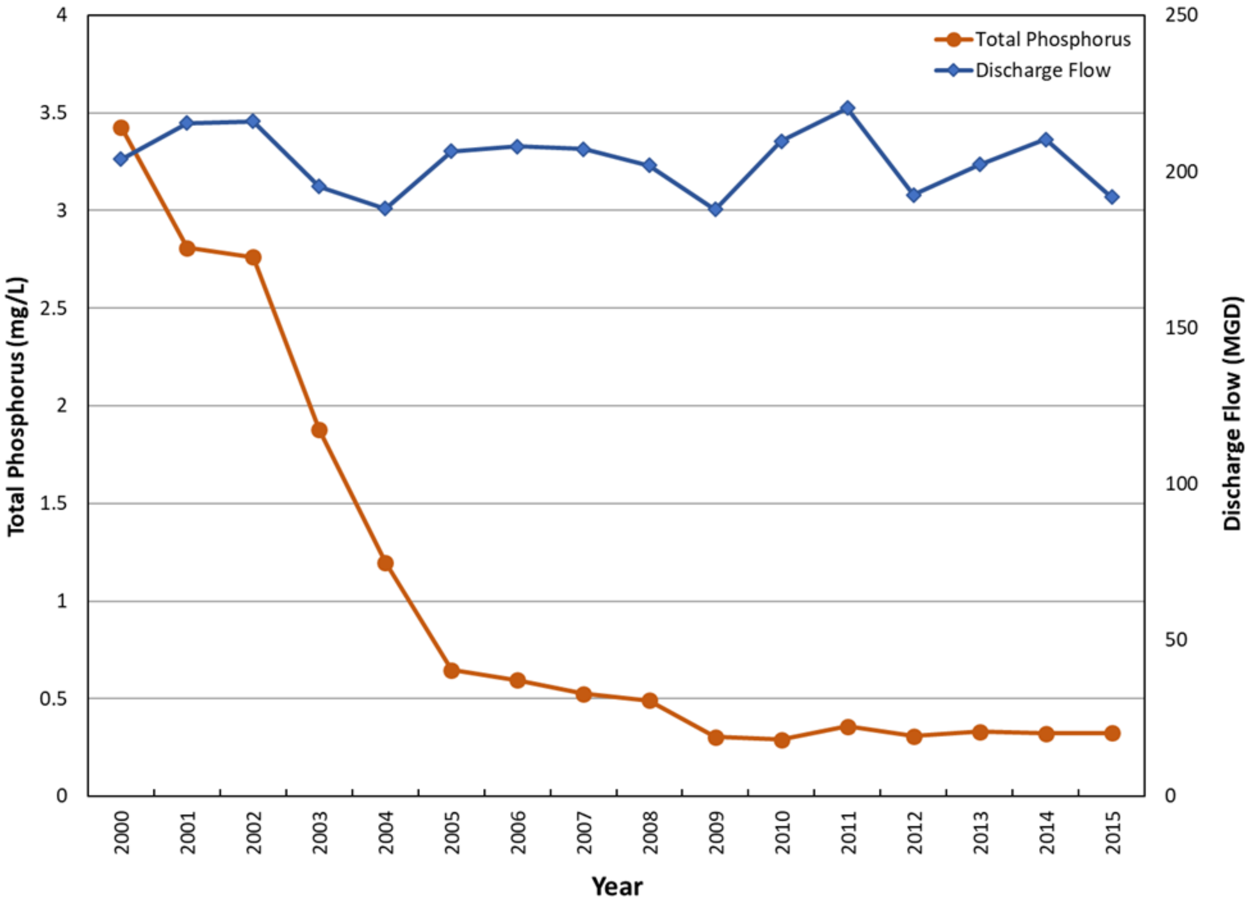
In part, the greater decreases in TP concentrations at Fort Snelling may reflect sediment and phosphorus trapping and deposition in the lower Minnesota River channel, especially during periods of lower flow. However, TP reductions in Lower Minnesota River tributaries may also play a role. Although these tributaries (Bevens, Bluff, Carver, Nine Mile, Riley, and Sand Creeks and Credit River) are amongst those metro area tributaries with the highest TP concentrations (MCES, 2014), none are currently listed by MPCA (2016a) as impaired for eutrophication. A recent trend analysis (MCES, 2014) determined that TP concentrations have consistently decreased in all of these Lower Minnesota River tributaries, with long-term reductions ranging from 27%-59%. Given the close relationship between TSS and TP concentrations, it is likely that the numerous TSS-related TMDL projects that have been successfully implemented by local water resources management organizations to address TSS impairments in Lower Minnesota River tributaries have also been beneficial for reducing TP concentrations.

In the St. Croix River, the greater decrease in TP concentration (32%) occurred at the downstream Prescott site, although a significant decrease (26%) was also apparent upstream at Stillwater. In large part, the greater decrease at Prescott may reflect sediment and phosphorus trapping and deposition in the 23-mile length of Lake St. Croix. Lafrancois et al. (2009) also noted slight but significant TP concentration reductions at Stillwater and Prescott during the 1976-2004 period. Although the overall magnitudes of those TP trends were not determined, the rate of change in TP concentrations was -0.0002 mg/L/year at both Stillwater and Prescott.

The decreasing TP trends in the three major metro area rivers are likely a reflection of multiple efforts to reduce phosphorus inputs to Minnesota's surface waters. In 1977, Minnesota implemented a ban on phosphorus in laundry detergents, with the objective of reducing phosphorus concentrations and loads from WWTPs discharging to the state's surface waters. In 2010, Minnesota implemented a ban on phosphorus in automatic dishwasher detergents, also with the objective of reducing WWTP phosphorus contributions to surface waters. The Minnesota Phosphorus Lawn Fertilizer Law regulates the use of phosphorus lawn fertilizer, with the intent of reducing phosphorus enrichment of surface waters. This prohibition went into effect in 2004 in the Twin Cities metro area, and statewide in 2005. As a result of this law, the amount of phosphorus contained in fertilizer used decreased from 292 tons in 2003 to 151 tons in 2006, a 48% reduction (MDA, 2007).

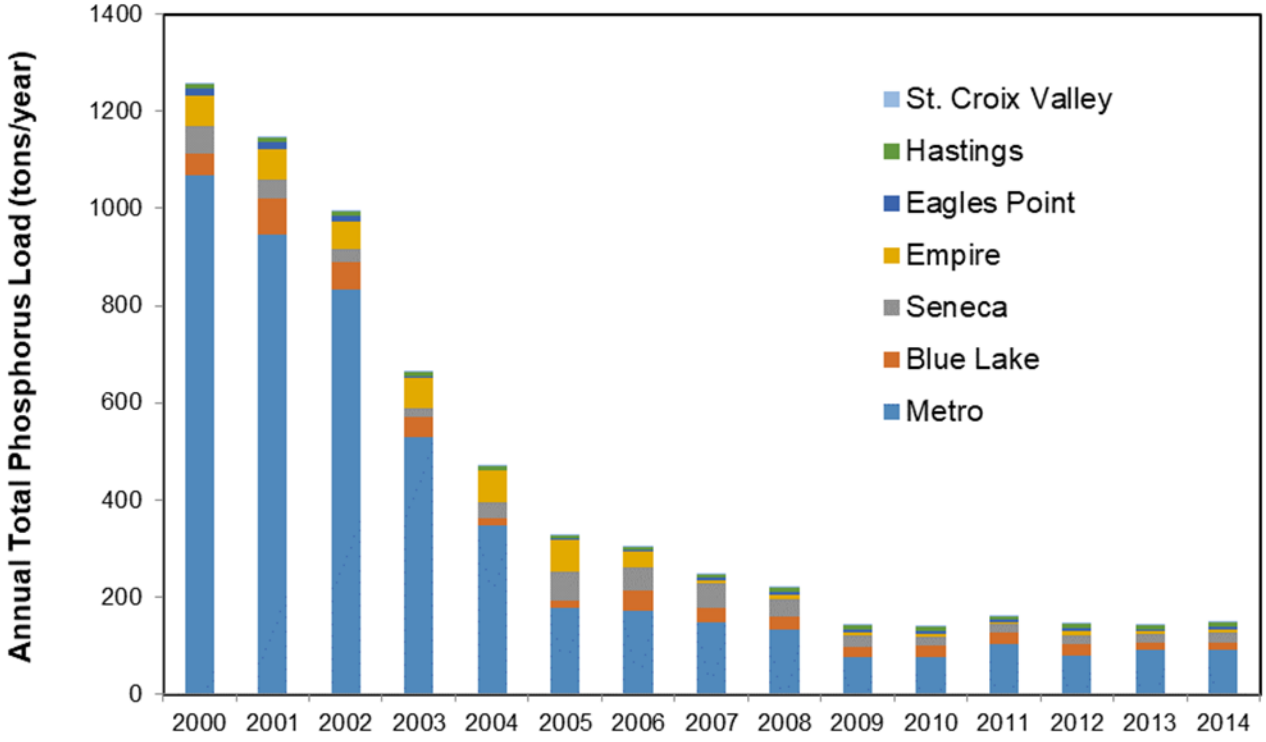
However, the greatest benefit gained and a major reason for decreasing TP trends in the three major metro area rivers has been the implementation of phosphorus removal technology at WWTPs, including the seven MCES WWTPs discharging to the Mississippi, Minnesota, and St. Croix rivers. In 2000, MPCA adopted a strategy for reducing phosphorus in WWTP discharges via limits on TP concentrations and loads in NPDES permits. In response to this strategy, MCES began implementing Bio-P removal technology at the Metro WWTP in 2000, with 100% implementation complete in 2003. As a result, TP concentrations in the Metro WWTP discharge have decreased from 3.4 mg/L in 2000 to 0.3 mg/L in 2015 (Figure 89), and TP loads have decreased from 1,067 tons/year in 2000 to 90 tons/year in 2014, a 92% reduction.

Figure 89. Annual Mean Metro Wastewater Treatment Plant Discharge Flow and Total Phosphorus Concentrations, 2000-2015



Since 2003, Bio-P removal technology has also been successfully applied at other MCES WWTPs, including the Blue Lake and Seneca WWTPs on the Minnesota River, and the Empire and Eagles Point WWTPs on the Mississippi River. Since 1973, the St. Croix Valley WWTP on the St. Croix River has used alum treatment for phosphorus removal to meet a TP discharge limit of 0.8 mg/L. The combined investments in phosphorus removal at MCES WWTPs have resulted in an 88% reduction in TP loads discharged to the three major metro area rivers since 2000 (Figure 90). Statewide, the MPCA reports a 67% reduction in annual TP loads from all WWTPs during the 2000-2016 period (MPCA, 2017c). Edlund et al. (2009) noted that, within the St. Croix River Basin, improvements in wastewater treatment technology resulted in a 49% decrease in TP loads from the 1960s to the 1990s.

Figure 90. Annual Total Phosphorus Loads from MCES Wastewater Treatment Plants, 2000-2014



On average, TP concentrations have decreased by 44%, 48% and 29%, respectively, in the metro area Mississippi, Minnesota, and St. Croix rivers during the 1976-2015 period. These decreasing TP trends across all three rivers are consistent with other reported results, including those by MPCA (2002), MCES (2004), Lafrancois et al. (2009), Lafrancois et al. (2013), and Weller and Russell (2016). As noted above, efforts to reduce phosphorus in statewide and metro area WWTP discharges have contributed greatly to the decreasing TP concentrations noted in the three metro area rivers. TP reductions in metro area tributaries (MCES, 2014) and benefits gained from the Minnesota Phosphorus Lawn Fertilizer Law have likely played a role as well. Given the magnitude of the TP trends observed and the dominant influence of the Minnesota River on TP concentrations at most metro area monitoring sites, it is possible that improvements in agricultural and land management practices (contour plowing, conservation tillage, Conservation Reserve Program, stream bank stabilization, riparian buffers) are also responsible for decreasing TP concentrations (Lafrancois et al., 2013). Continued attention to nonpoint sources of TP and TSS (and to factors that mediate their delivery to surface water, including climate and artificial drainage) is clearly warranted (Lafrancois et al., 2013). In addition, continuing long-term monitoring and data analysis are needed to determine if the observed TP reductions are sustainable.

Corrected Chlorophyll-*a* (Chl-*a*)

Chl-*a* is a pigment that is necessary for photosynthesis in plants, including algae in surface waters. Chl-*a* refers to pheophytin-corrected chlorophyll-*a*, which represents the amount of living algae in the water. Algae growth depends on factors such as nutrient and light availability, temperature, and pH. In freshwater systems, phosphorus is typically the limiting factor that controls algae growth (Dillon and Rigler, 1974). Elevated nutrient levels (both phosphorus and nitrogen) can cause excessive algae growth, which has detrimental effects on surface waters. As algae die off, the decomposition process consumes oxygen, potentially causing uninhabitable conditions for most aquatic life. Extensive growth (algal blooms) of some types of algae can also cause poor drinking water quality, unpleasant environments for recreation, and potential health impacts on people and animals (MPCA 2004b).

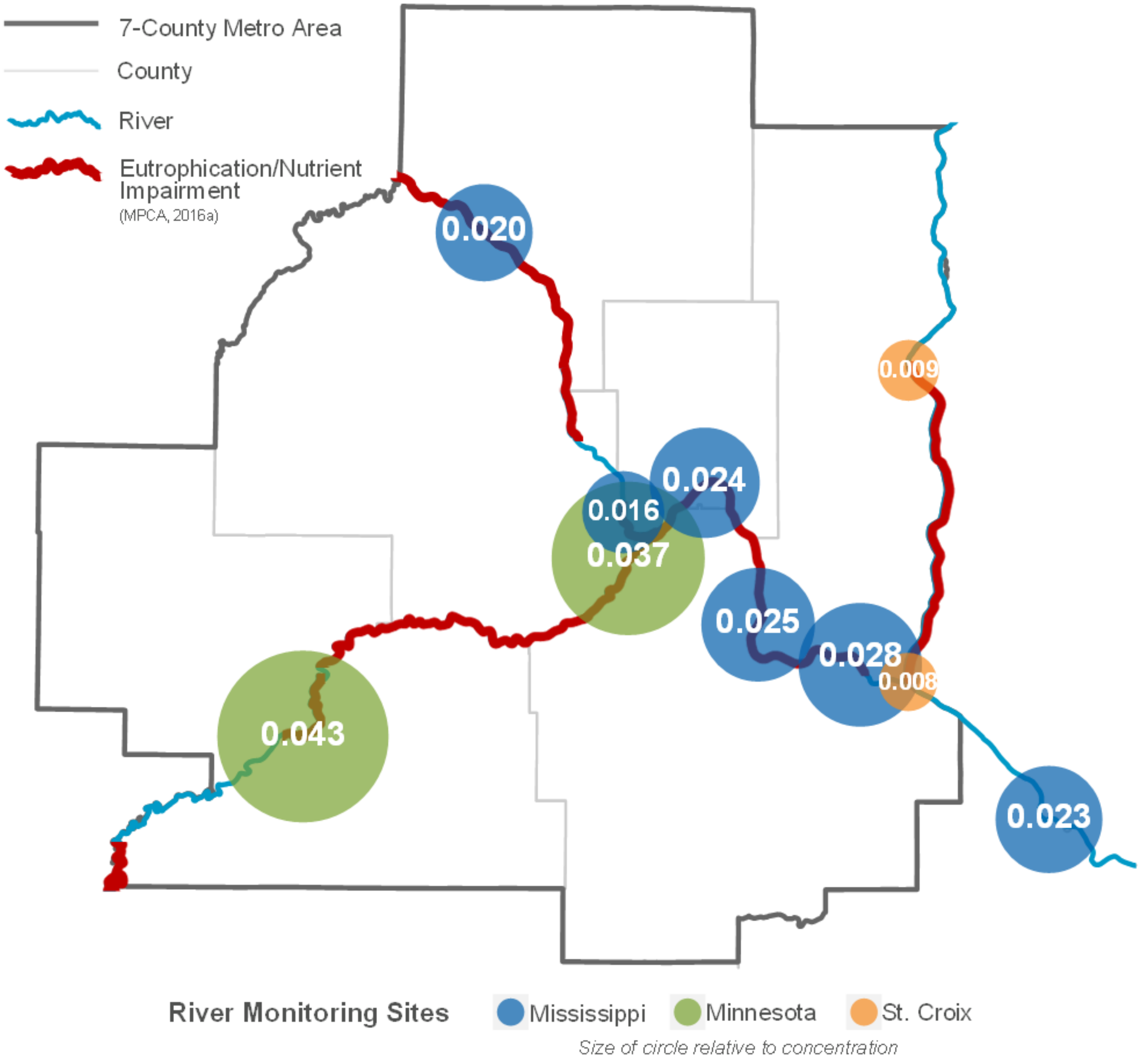
Recent Conditions. Figure 91 displays the median Chl-*a* concentrations measured from 2006-2015 at each of the river monitoring sites in the metro area. As the three major rivers entered the metro area, the Minnesota River had the highest 10-year median Chl-*a* concentration (0.043 mg/L at Jordan), the St. Croix River had the lowest Chl-*a* concentration (0.009 mg/L at Stillwater), and the Mississippi River had an intermediate Chl-*a* concentration (0.020 mg/L at Anoka). Across the three rivers, this is the same pattern as that observed for concentrations of nutrients related to Chl-*a* production (TP – Figure 87, TN – Figure 93, and NO_3 – Figure 95). Hence, these differences in nutrient concentrations between the three rivers were likely responsible for the differences in Chl-*a* concentrations, since nutrient availability is correlated with algae growth (Heiskary and Markus, 2001).

Relationships between nutrients and Chl-*a* in Minnesota's rivers are complex. The availability of phosphorus and nitrogen is a key factor influencing algae growth. However, phosphorus and nitrogen often exist in several aquatic forms, and not all forms are available for uptake and algal growth. Also, the ratios between the forms of phosphorus and nitrogen in rivers can shift due to many different biotic and abiotic factors (James and Larson, 2008). Interrelationships between nutrients and Chl-*a* can also vary based on other factors, such as watershed size, river flow, water residence time, and light availability (Heiskary and Markus, 2001; MCES, 2002; 2010).

In the metro Mississippi River, 10-year median Chl-*a* concentrations were lowest in the upstream portion of the river (Anoka and Lock and Dam 1), as was the case with TP concentrations. The high Chl-*a* concentration in the Minnesota River (0.037 mg/L at Fort Snelling) caused the Chl-*a* concentration to increase in the Mississippi River between Lock and Dam 1 (0.016 mg/L) and Saint Paul (0.024 mg/L). Moreover, the Minnesota River influenced Chl-*a* concentrations throughout Pool 2 of the Mississippi River, although slightly increased Chl-*a* concentrations at Grey Cloud Island and Lock and Dam 2 may also reflect Metro WWTP phosphorus contributions and algal growth due to longer water residence times in Spring Lake and lower Pool 2. Downstream from Lock and Dam 2, the lower Chl-*a* concentration in the St. Croix River (0.008 mg/L at Prescott) provided a dilution effect in the Mississippi River, causing Chl-*a* to slightly decrease between Lock and Dam 2 (0.028 mg/L) and Lock and Dam 3 (0.023 mg/L).

In a study of phosphorus and chlorophyll relationships in 116 temperate streams around the world, Van Nieuwenhuyse and Jones (1996) found that the highest summer average total chlorophyll-*a* concentration occurred in the Minnesota River at Jordan (0.170 mg/L during the 1976-1992 period). In the metro Minnesota River, the 10-year median Chl-*a* concentration decreased from upstream (0.043 mg/L at Jordan) to downstream (0.037 mg/L at Fort Snelling). Since TP, TN, and NO_3 concentrations increased along this same stretch of river, it is probable that nutrients were sufficiently available and some factor beyond nutrient availability was limiting algae growth. Although TSS concentrations decreased from Jordan to Fort Snelling, they remained high enough to limit light availability for algae growth. Light limitation is greater during high flows when TSS concentrations increase, and algae growth can resume when river flows and TSS concentrations decrease (Heiskary and Markus, 2001; MPCA, 2014). James (2007) suggests that Chl-*a* concentrations are lower when TSS concentrations are higher, not because of light restriction, but because the high flows that bring higher TSS concentrations also decrease water residence time in the lower Minnesota River, thereby flushing away the algae.

Figure 91. Median Corrected Chlorophyll-*a* Concentrations (mg/L) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



The decrease in median Chl-*a* concentrations between the upstream and downstream sites on the Minnesota River may also indicate that algae were generally dying off or settling out of the water column. During low flows, James and Larson (2008) reported that Chl-*a* (a proxy of living algae) decreased while pheophytin-*a* (a by-product of degraded chlorophyll-*a*) increased, indicating net degradation of algae. James (2007) suggested that circulation through Xcel Energy's Black Dog Generating Station, which partially diverts Minnesota River water for cooling purposes at Burnsville, might be contributing to algal senescence. Additionally, the deeper navigation channel and slower current velocity in the lower 22 miles of the Minnesota River allow suspended material, including any floating algae, to settle out (MPCA, 1985; 2004a).

In the St. Croix River, the median Chl-*a* concentration was slightly higher at Stillwater (0.009 mg/L) than at Prescott (0.008 mg/L). From upstream to downstream in this river reach (Lake St. Croix), TP and TSS concentrations decreased slightly, while TN and NO_3 concentrations increased slightly. Like the relationship between TP and Chl-*a* in the lower Minnesota River, Lafrancois et al. (2009) propose that TP concentrations in Lake St. Croix are sufficiently abundant, and some other factor such as light availability may be responsible for limited algal growth. Settling of suspended materials, which occurs due to slower water velocities and much deeper water depth in Lake St. Croix, likely accounts for lower Chl-*a* concentrations.

The MPCA has established Chl-*a* criteria as part of Minnesota's eutrophication standards (Minn. Rules Chapter 7050; MPCA, 2015d; Heiskary and Wilson, 2008). Chl-*a* is one of the response criteria considered for both the river and lake eutrophication standards. A eutrophication impairment exists if the criteria for the causative variable, TP, as well as the criteria for one or more response parameters, are exceeded. The criteria for Chl-a at each of the river monitoring sites are listed in Table 30. The criteria for the sites on the St. Croix River are defined by the lake eutrophication standard instead of the river standard because of Lake St. Croix. The criteria are set for multi-year summer average concentrations, so they are not comparable to the 10-year median concentrations in Figure 91. Regardless, seven of the 10 river monitoring sites are on river reaches that have been listed by MPCA as impaired for eutrophication, as shown in Figure 91 (MPCA, 2012; 2016a).

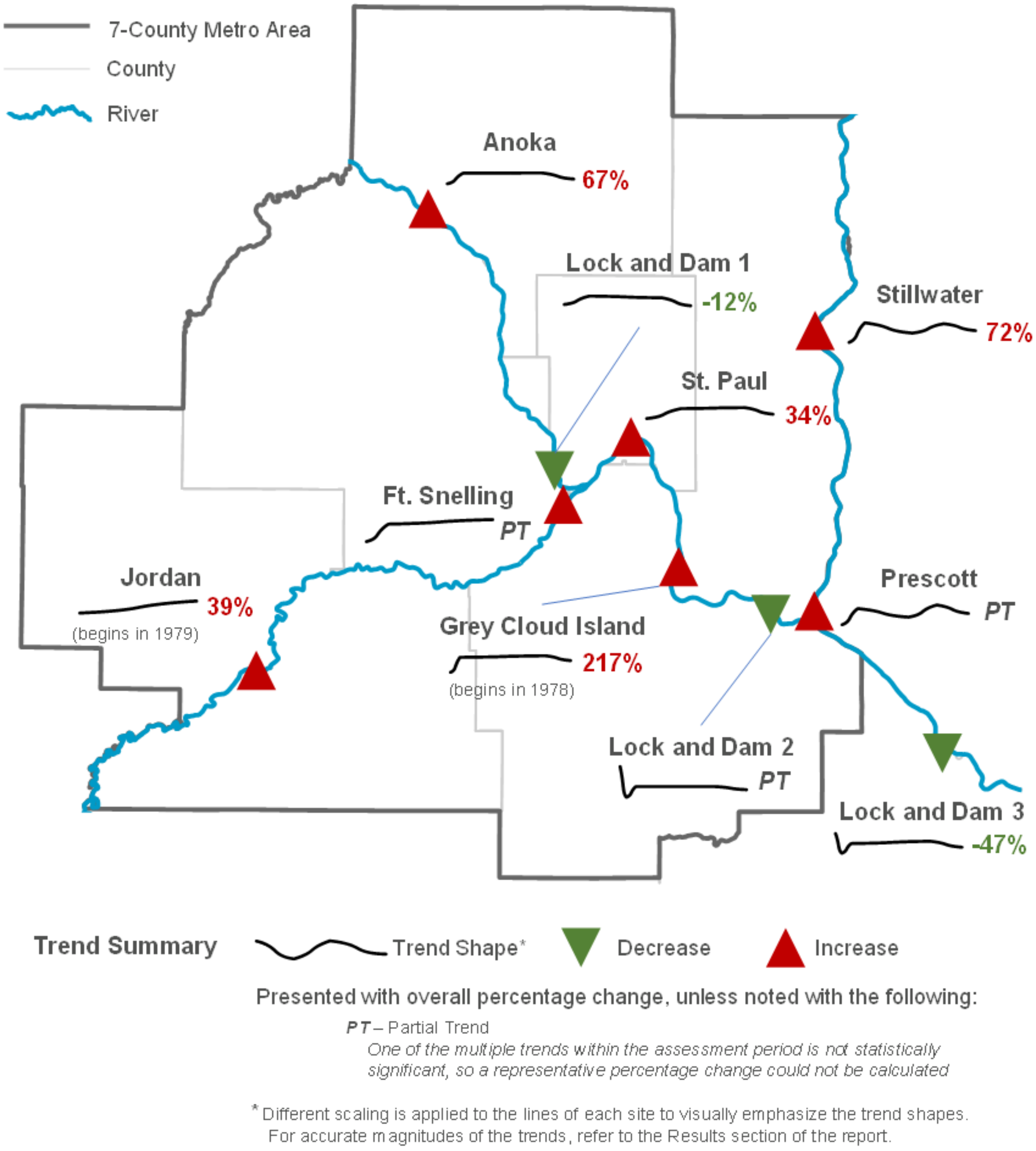
Table 30. Eutrophication Criteria at Metro Monitoring Sites - Corrected Chlorophyll-*a*

Site	Chl-*a* Criteria (mg/L) [a]
Mississippi River	
Anoka	0.018
Lock and Dam 1	0.035
Saint Paul	0.035
Grey Cloud Island	0.035
Lock and Dam 2	0.035
Lock and Dam 3	0.035
Minnesota River	
Jordan	0.040
Fort Snelling	0.040
St. Croix River	
Stillwater	0.014
Prescott	0.014

[a] Criteria are from Minnesota's river and lake eutrophication standards. Chl-*a* is one of the response criteria within the eutrophication standards. The values represent multi-year summer averages.

40-Year Trends. Figure 92 displays overall trends in flow-adjusted Chl-*a* concentrations in the metro area Mississippi, Minnesota, and St. Croix rivers. Overall, Chl-*a* concentration trends were mixed across the three rivers, with no consistent regional trend pattern evident. Substantial increases in Chl-*a* concentrations occurred at river entry points to the metro area, including a 67% increase in the Mississippi River at Anoka, a 39% increase in the Minnesota River at Jordan, and a 72% increase in the St. Croix River at Stillwater. MCES (2004) previously evaluated Chl-*a* concentration trends at river entry points to the metro area during the 1976-2002 period, finding no trends in the Mississippi River at Anoka and the Minnesota River at Jordan, but a slight increase (8%) in the St. Croix River at Stillwater (Table 31). However, Lafrancois et al. (2009) found no significant trend in Chl-*a* concentrations at Stillwater during the 1976-2004 period.

Figure 92. Flow-Adjusted Corrected Chlorophyll-*a* Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers, 1976-2015



Presented with overall percentage change, unless noted with the following:

PT – Partial Trend
One of the multiple trends within the assessment period is not statistically significant, so a representative percentage change could not be calculated

* Different scaling is applied to the lines of each site to visually emphasize the trend shapes. For accurate magnitudes of the trends, refer to the Results section of the report.

Table 31. Results from Past Studies of Chlorophyll-*a* Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers

Author	Study Period	Trend Analysis Method	Anoka	Lock and Dam 1	Saint Paul	Grey Cloud Island	Lock and Dam 2	Lock and Dam 3	Jordan	Fort Snelling	Stillwater
MCES, 2004	1976-2002	SEAKEN	NT*					8%*	NT*		8%*
Lafrancois, 2013	1976-2005	SEAKEN	NT	NT	14%	23%	NT			22%	

SEAKEN: nonparametric Seasonal Kendall test

NT: no significant trend

* Locally-weighted scatterplot smoothing (LOWESS) procedure used to remove effects of flow on concentration

Downstream from the entry point at Anoka, trends in Mississippi River Chl-*a* concentrations were variable, decreasing at Locks and Dams 1, 2, and 3, and increasing at Saint Paul and Grey Cloud Island. Using a different statistical method to assess metro area Mississippi River Chl-*a* trends during the 1976-2005 period, Lafrancois et al. (2013) noted no trends in Chl-*a* concentrations at Locks and Dams 1 and 2 and slight increases in Chl-*a* concentrations at Saint Paul and Grey Cloud Island. MCES (2004) found an 8% reduction in Chl-*a* concentrations at Lock and Dam 3 during the 1976-2002 period.

In the Minnesota River, a partial increasing trend in Chl-*a* concentrations was noted at Fort Snelling, consistent with the increasing trend (39%) evident at Jordan. Lafrancois et al. (2013) also found an increasing trend in Chl-*a* concentrations (22%) at Fort Snelling during the 1976-2005 period.

In the St. Croix River, a partial increasing trend in Chl-*a* concentrations was evident at Prescott, consistent with the increasing trend (72%) evident at Stillwater. The relatively high percentage increase at Stillwater is primarily a reflection of a small absolute increase in a Chl-*a* concentration that is one of the lowest of all metro area river concentrations (Figure 91). Lafrancois et al. (2009) noted that an increasing trend in Chl-*a* concentrations was apparent at Prescott during the 1976-2004 period. While the overall magnitude of the trend at Prescott was not determined, the rate of change in Chl-*a* concentrations was 0.046 mg/L/year.

As discussed above, Chl-*a* concentrations are generally related to several environmental factors (nutrient and TSS concentrations, light availability, temperature, pH, and flow), although phosphorus is typically the limiting factor that controls algae growth in freshwater systems (Dillon and Rigler, 1974). During the 1976-2015 period, TP concentrations decreased at all Mississippi, Minnesota, and St. Croix River monitoring sites in the metro area. However, corresponding decreases in Chl-*a* concentrations were not observed, as might be anticipated. Rather, Chl-*a* concentrations increased in the Minnesota and St. Croix rivers, while Chl-*a* concentration trends were mixed in the Mississippi River. Previous studies (MCES, 2004; Lafrancois et al., 2009; Lafrancois et al., 2013) have also noted the lack of a relationship between TP and Chl-*a* trends in metro area rivers.

QWTREND, the statistical tool that MCES uses to evaluate long-term trends in water quality parameters, can also be used to provide detailed information on sub-trends that may occur within a long-term period such as 1976-2015 (refer to the “Appendix”). As noted in the TP discussion, a major reason for the decreasing TP trends in the three major metro area rivers has been the implementation of phosphorus removal technology at Minnesota WWTPs, including the seven MCES WWTPs discharging to the metro area Mississippi, Minnesota, and St. Croix rivers. These TP reductions at WWTPs have occurred after 2000, when the MPCA adopted a strategy for reducing phosphorus in WWTP discharges via limits on TP concentrations and loads in NPDES permits. If Chl-*a* concentration trends are evaluated for the most recent sub-trend periods after 2000, a different trend pattern emerges, which is more consistent with the TP trends noted. A summary of these most recent Chl-*a* sub-trends is presented in Table 32.

Table 32. QWTREND Sub-Trends in Flow-Adjusted Corrected Chlorophyll-*a* Concentrations in the Mississippi, Minnesota, and St. Croix Rivers

Site	Sub-Trend Period	Chl-a Concentration Trend (%)
Anoka	2006-2015	-34
Lock and Dam 1	2007-2015	-46
Saint Paul	2007-2015	-28
Grey Cloud Island	2008-2015	-22
Lock and Dam 2	2006-2015	NT
Lock and Dam 3	2006-2015	-28
Jordan	1979-2015	39
Fort Snelling	1983-2015	NT
Stillwater	2006-2015	-20
Prescott	2006-2015	NT

NT: no significant trend

In the Mississippi and St. Croix rivers, Chl-*a* concentrations have generally decreased during the most recent sub-trend periods, suggesting that post-2000 TP reductions at MCES and Minnesota WWTPs have resulted in decreasing Chl-*a* concentrations. In the Mississippi River, greater decreases in recent Chl-*a* concentrations were apparent at Anoka and Lock and Dam 1, while smaller decreases have occurred at monitoring sites downstream from the confluence of the Minnesota River, which delivers higher concentrations of TP, Chl-*a*, and TSS to the Mississippi River. Smaller decreases in Chl-*a* concentrations at the downstream sites might be attributed to higher TSS concentrations at these locations (Figure 84), which limit light availability for algal production.

In the Minnesota River, a continuously increasing Chl-*a* concentration trend (39%) is apparent at Jordan during the entire 1979-2015 monitoring period, with QWTREND unable to detect any sub-trends within this period. The increase in Chl-*a* concentrations at Jordan may be due to increased light availability for algal production, as TSS concentrations have decreased by 37% (Figure 85). Although TP concentrations at Jordan have decreased by 44% during the 1979-2015 period (Figure 88), concentrations have remained high enough such that phosphorus is not limiting algal productivity.

In this study, Chl-*a* concentrations exhibited inconsistent and/or mixed trends across the three regional rivers, depending on the length of the assessment period. Another contributing factor is the complex relationship between Chl-*a* and other environmental variables associated with these large rivers (noted above). As well, large, unexplained changes in Chl-*a* concentrations occurred during the 1976-1980 period at all monitoring sites except Jordan, confounding the long-term trend analysis (1976-2015). Given that (1) long-term Chl-*a* concentration trends are inconsistent with long-term TP concentration trends, (2) nutrient impairments exist on all three regional rivers, and (3) algal blooms are a growing regional and national concern, further exploration of Chl-*a* trends in metro area rivers is warranted. Continuing long-term monitoring and data analysis are needed to determine whether consistent reductions in Chl-*a* concentrations are apparent in the future.

Total Nitrogen (TN)

Nitrogen is a nutrient that exists naturally in rivers and is important for plant growth. Nitrogen cycles between different forms in the environment, and TN is the combination of all forms, both organic and inorganic. In Minnesota's surface waters, the primary forms of nitrogen are (MPCA, 2013):

- Organic Nitrogen – nitrogen that is present in living or dead organic matter
- Nitrate-Nitrogen (NO_3) – a highly soluble, mobile, inorganic form of nitrogen
- Nitrite-Nitrogen (NO_2) – an intermediate inorganic form of nitrogen that is generally present at very low concentrations in water
- Ammonia-Nitrogen (NH_3) – a product of degraded organic nitrogen that is generally present at relatively low concentrations in water

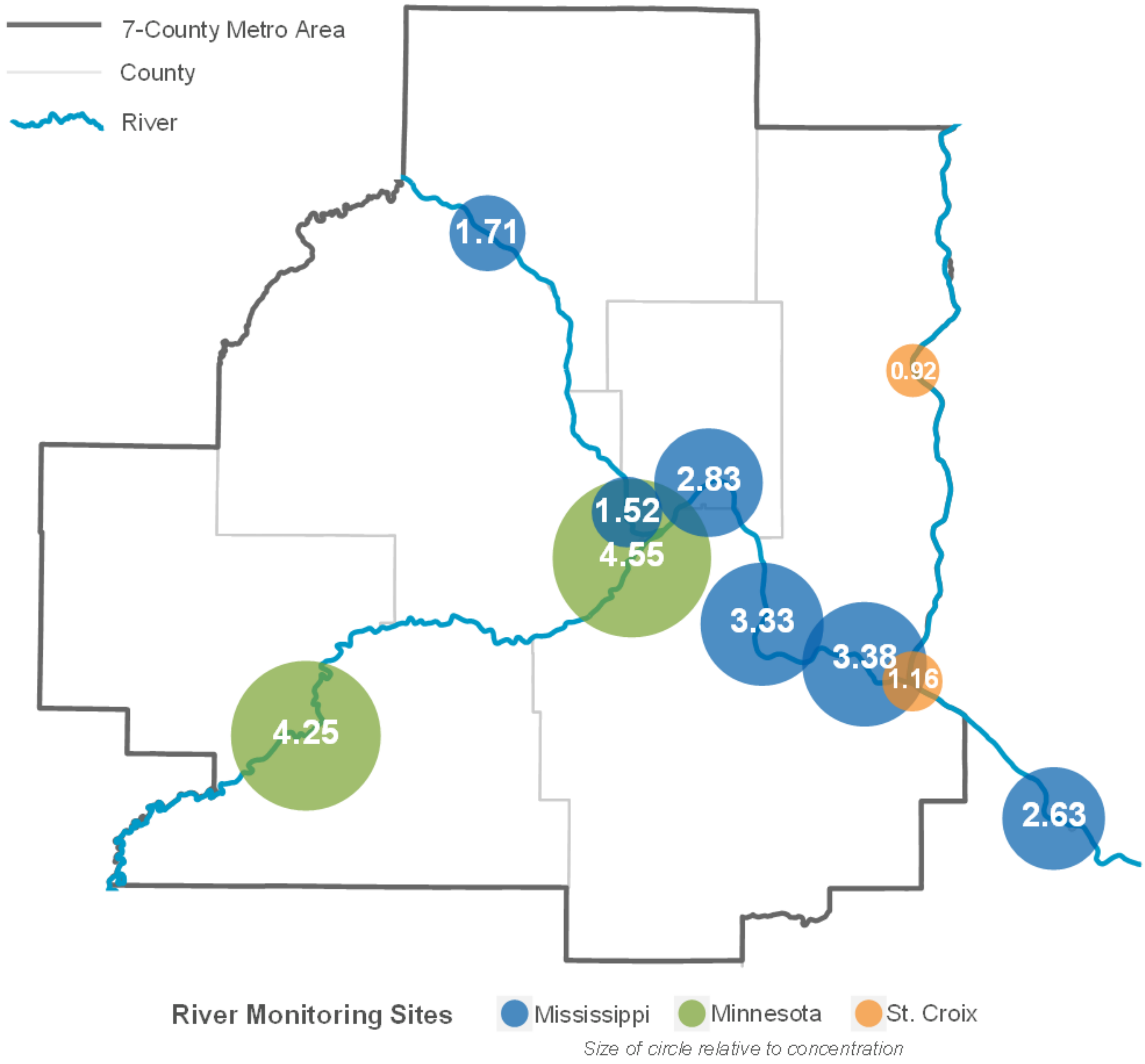
TN concentrations are generally low in natural environments, but human activity can elevate TN concentrations beyond natural levels (Dubrovski et al., 2010). The amount of TN entering Minnesota's surface waters can vary considerably based on precipitation and flow, doubling in wet years and decreasing by half in dry years when compared to an average year (MPCA, 2013). High TN concentrations can be detrimental to both human and environmental health (MPCA, 2013), as detailed later in the discussions of NO_3 and NH_3.

Croplands are the main source of TN in Minnesota's surface waters, contributing 72% of the statewide TN load (MPCA, 2013). Specifically, 37% of the cropland load is from tile drainage, 30% is from groundwater under cropland (nitrogen leaches into groundwater, which can eventually flow into surface waters), and 5% is from cropland surface runoff. The remaining TN load comes from other sources, including municipal WWTPs, atmospheric deposition, forests, septic systems, and urban runoff. The proportion of TN sources varies between watersheds and can change under different flow conditions; the portion from croplands is higher in wet years and lower in dry years, whereas the portion from WWTPs increases in dry years (MPCA, 2013; 2014).

Recent Conditions. Figure 93 displays the median TN concentrations measured from 2006-2015 at each of the river monitoring sites in the metro area. As the three major rivers entered the metro area, the Minnesota River had the highest 10-year median TN concentration (4.25 mg/L at Jordan), the St. Croix River had the lowest TN concentration (0.92 mg/L at Stillwater), and the Mississippi River had an intermediate TN concentration (1.71 mg/L at Anoka). Areas in Minnesota which are high sources of TN have more row crops, tile drainage, and animal density, while in contrast, areas which are low sources of TN have more wetlands, forests, grasslands, and soil organic matter (MPCA, 2013). With the Minnesota River Basin having the highest proportion of agricultural land and the St. Croix River Basin having the highest combined proportion of grass, forests, and wetlands, it follows that the Minnesota River and St. Croix River would have the highest and lowest median TN concentrations, respectively. With a more even mix of agriculture, forests, and wetlands in the Upper Mississippi Basin (see "Study Area and Scope"), the metro Mississippi River has an intermediate median TN concentration.

Agriculture is a dominant source of TN in all three river basins. The MPCA has estimated that, in a year with average precipitation and river flow, cropland accounts for 49%, 89%, and 62% of the TN loads in the Upper Mississippi River, Minnesota River, and St. Croix River, respectively (MPCA, 2013). In the St. Croix River Basin, forests contribute 19% of the TN load. In the Upper Mississippi River Basin, point sources contribute 21% of the TN load, due to presence of WWTPs, including the large MCES facilities serving the metro area.

Figure 93. Median Total Nitrogen Concentrations (mg/L) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



In the metro area of the Mississippi River, the 10-year median TN concentrations were lowest in the upstream portion of the river (Anoka and Lock and Dam 1). Typically, TN reductions are minimal in the Mississippi River, unless there are slow-moving portions of the river where water residence time is high, such as in pools above locks and dams (MPCA, 2013). With an 11% reduction in TN concentration noted from Anoka to Lock and Dam 1, it's possible that conditions in Pool 1 (above Lock and Dam 1) were favorable for TN loss, due to conversion to atmospheric nitrogen via denitrification and/or settling out of organic nitrogen.

The high TN concentration in the Minnesota River (4.55 mg/L at Fort Snelling) caused the median TN concentrations in the Mississippi River to increase 86% between Lock and Dam 1 (1.52 mg/L) and Saint Paul (2.83 mg/L). This Minnesota River impact influenced TN concentrations in the entirety of Pool 2 in the Mississippi River, although the higher concentrations at Grey Cloud Island and Lock and Dam 2 also reflected TN contributions from the Metro WWTP. The lower TN concentration in the St.

Croix River (1.16 mg/L at Prescott) provided a dilution effect in the Mississippi River, causing TN to decrease 22% between Lock and Dam 2 (3.38 mg/L) and Lock and Dam 3 (2.63 mg/L).

The TN concentration increased slightly in the Minnesota River as it passed through the metro area, with a 7% increase noted between Jordan and Fort Snelling (Figure 93). The elevated TN concentrations in the Minnesota River were dominated by high NO_3 concentrations, which also increased slightly (3%) between Jordan and Fort Snelling (Figure 95). James (2007) found that the lower Minnesota River was a minor net source of NO_3 in 2004 and 2005 and a minor sink in 2006, and he suggests that NO_3 moves through this river reach with little transformation. Other forms of nitrogen may have also contributed to the slight increase in TN between Jordan and Fort Snelling. Nitrogen influxes from tributaries, urban stormwater runoff, the Seneca and Blue Lake WWTPs, and the Xcel Energy Black Dog Generating Station, plus nitrogen processing within the river are all likely affecting TN concentrations.

In the St. Croix River, the median TN concentration increased 26% between Stillwater and Prescott. This was likely due to a substantial increase in the NO_3 concentration (142%) between these two sites (Figure 95). Lafrancois et al. (2009) suggested that there are significant point and nonpoint sources contributing NOx (the sum of NO_3 and NO_2, of which NO_2 is generally a negligible amount) to Lake St. Croix, such as WWTPs and nitrogen-rich groundwater. Additionally, of the 12 major tributaries within the St. Croix River watershed, the two with the highest NO_3 concentrations during baseflow conditions, as well as the two with the highest percentages of agricultural land use, are the Kinnickinnic and Willow rivers (Lenz et al., 2003). These two tributaries drain directly into Lake St. Croix between Stillwater and Prescott.

WWTPs account for 9% of the nitrogen load to Minnesota surface waters in an average year, and nearly half of this loading occurs within the metro area (MPCA, 2013), where MCES WWTPs are contributing sources. Based on Figure 93, the Metro WWTP had a notable impact on TN concentrations in Pool 2 of the Mississippi River. While other MCES WWTPs are also TN sources to metro area rivers, they did not appear to substantially increase median TN concentrations.

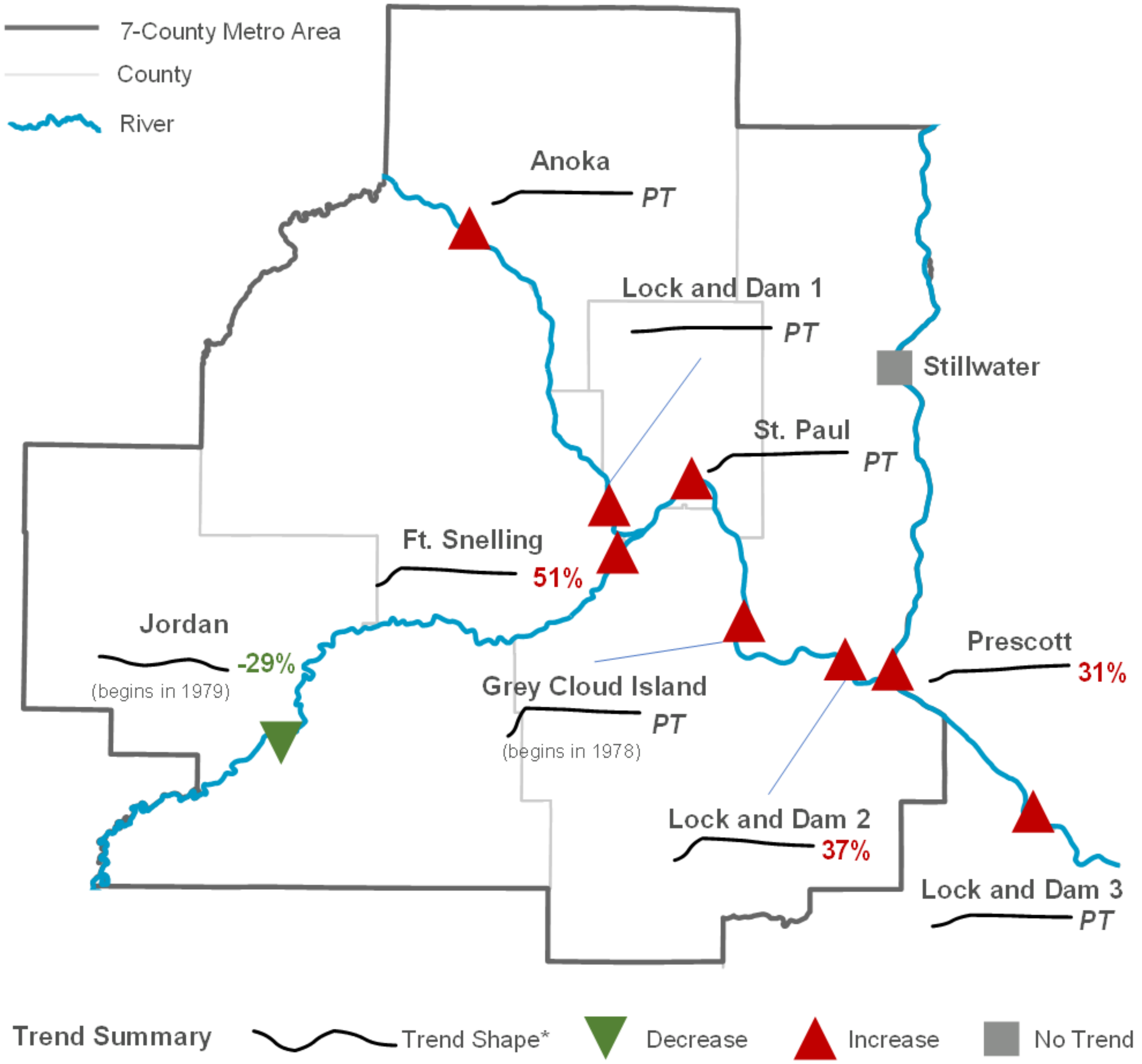
There are currently no Minnesota water quality standards for TN in rivers and streams. When the MPCA was developing eutrophication standards for rivers, relationships between TN and biological responses were obscured by TP concentrations, so the role of TN in eutrophication of Minnesota's rivers and streams is unclear (Heiskary and Bouchard, 2015). As a result, TN was not included as part of the eutrophication standard. However, there are water quality standards for specific forms of TN, and these are detailed in the discussions of NO_3 and NH_3.

40-Year Trends. Figure 94 displays overall trends in flow-adjusted TN concentrations in the metro area Mississippi, Minnesota, and St. Croix rivers. Trend results show that TN concentrations have generally increased across all three rivers during the past 40 years, indicating a decline in water quality.

At river entry points to the metro area, TN concentration trends are mixed, with a partial increase noted at the Mississippi River entry point (Anoka), a 29% decrease noted at the Minnesota River entry point (Jordan), and no trend apparent at the St. Croix River entry point (Stillwater).

In the Mississippi River, TN concentrations have increased at all sites during the last 40 years. Partial increasing trends were apparent at all sites except Lock and Dam 2, where a 37% increase was documented. Detailed sub-trend analyses (Table 40 through Table 45 found in the "Appendix") show that TN concentrations primarily increased during the first 7 to 16 years of the 40-year trend period, depending upon the site. After these early significant increases, TN concentrations exhibited little change (statistically non-significant) during the recent 24 to 33 years.

Figure 94. Flow-Adjusted Total Nitrogen Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers, 1976-2015



Presented with overall percentage change, unless noted with the following:

PT – Partial Trend
One of the multiple trends within the assessment period is not statistically significant, so a representative percentage change could not be calculated

* Different scaling is applied to the lines of each site to visually emphasize the trend shapes. For accurate magnitudes of the trends, refer to the Results section of the report.

In the Minnesota River, TN concentration trends were mixed, decreasing by 29% at Jordan but increasing by 51% at Fort Snelling. Detailed sub-trend analyses (Table 46 and Table 47 in the "Appendix") indicate a meandering, but overall downward, change in the TN concentration at Jordan. At Fort Snelling, a steep TN concentration increase (74%) from 1976-1982 was followed by a gradual decrease (13%) from 1983-2015.

In the St. Croix River, TN concentration trends were also mixed. No trend was evident at Stillwater, but a 31% increase was apparent at Prescott. Detailed sub-trend analyses (Table 48 and Table 49 in the "Appendix") show that the greatest increase in TN concentration at Prescott occurred from 1976 to 1982, while a gradual increase occurred from 1983 to 2015.

Using a different statistical method (seasonal Kendall test), Lafrancois et al. (2013) analyzed TN concentration trends during the 1976-2005 period, at the six Mississippi River sites and one Minnesota River site (Fort Snelling) evaluated in this report. Compared to the increasing TN trends noted at these locations in this report, Lafrancois et al. (2013) found no TN concentration trends at the same sites. In the St. Croix River, Lafrancois et al. (2009) found a decreasing trend in TN concentrations at Stillwater and an increasing trend in TN concentrations at Prescott during the 1976-2004 period.

Nitrate-Nitrogen (NO_3)

NO_3 is a form of nitrogen that is important for the growth of plants. It is very soluble in water, so it easily moves through the soil. Sources of NO_3 in soil and water include treated wastewater, septic systems, fertilizers, and precipitation. Often, NO_3 sources are originally in other forms of nitrogen, such as NH_3 or organic nitrogen in manure, fertilizers, and organic wastes. However, these forms are easily converted to NO_3 in oxygenated, warm, and moist conditions. NO_3 is the most common form of nitrogen in groundwater (MPCA, 2013), and is the main form of nitrogen in Minnesota's rivers when TN is elevated (Heiskary et al., 2013).

There are three main concerns with elevated NO_3 concentrations in water:

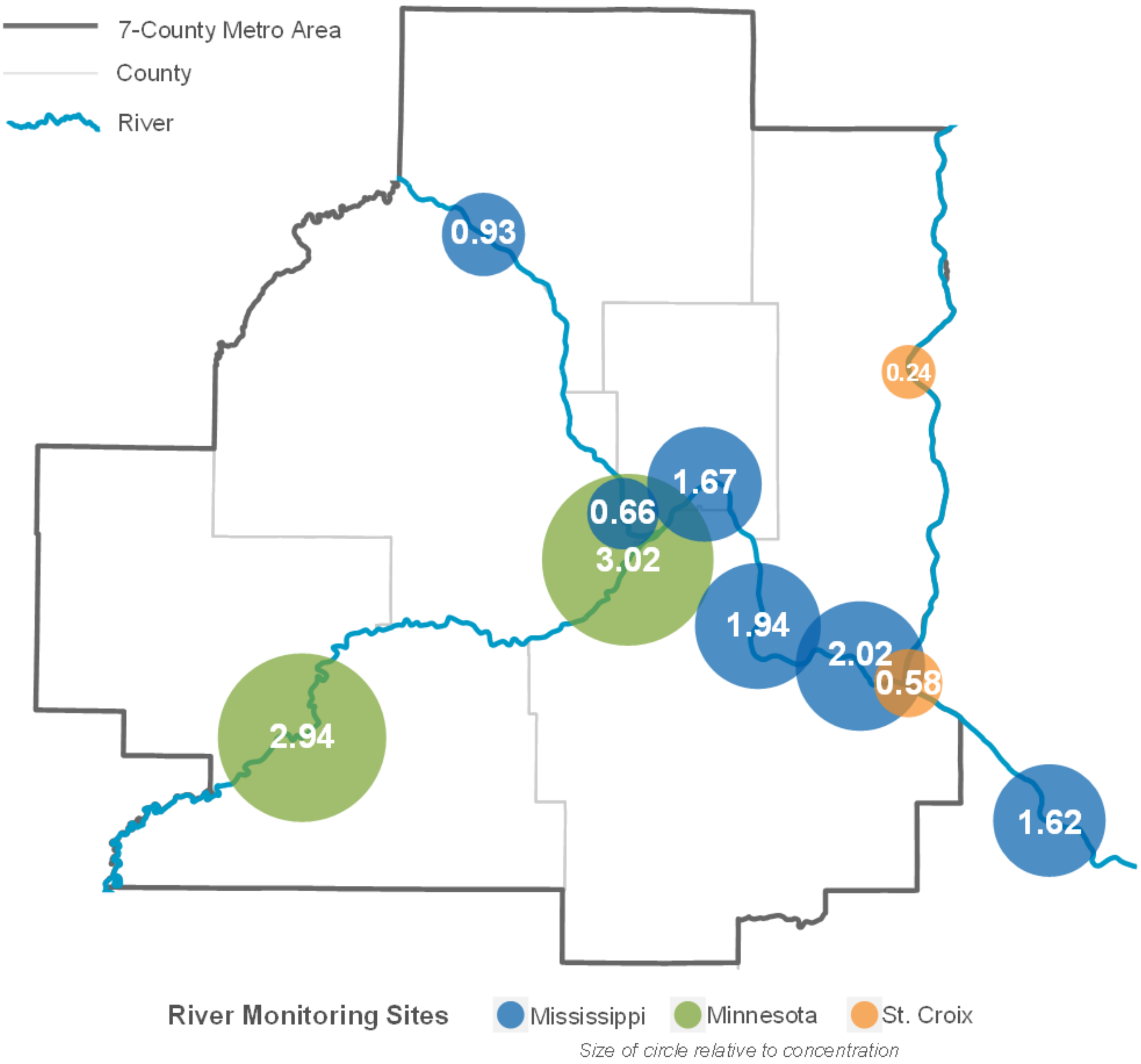
- Human health – NO_3 concentrations above the drinking water standard (10 mg/L) can cause human health risks, especially for infants ("blue baby syndrome"). High concentrations can cause methaemoglobinaemia, which reduces the ability of blood to transport oxygen throughout the body (WHO, 2016).
- Toxicity to aquatic life – High NO_3 concentrations can be harmful to the growth and development of aquatic life (Camargo and Alonso, 2006).
- Downstream eutrophication – NO_3 delivered by the Mississippi River contributes to the low-oxygen "Dead Zone" in the Gulf of Mexico (Alexander et al., 2000; Rabalais et al., 2002). Excess NO_3 in the Gulf creates massive algae blooms each year. Decomposition of these blooms reduces oxygen concentrations in the water (hypoxia), suffocating marine life. The section of the Mississippi River upstream from the Ohio River confluence contributes 33% of the nitrogen delivered by the river annually to the Gulf of Mexico (Alexander et al., 2008).

Recent Conditions. Figure 95 displays the median NO_3 concentrations measured from 2006-2015 at each of the river monitoring sites in the metro area. The pattern for 10-year median NO_3 concentrations across the metro area is very similar to that for 10-year median TN concentrations (Figure 93), as NO_3 is typically the dominant form of nitrogen in rivers that have excess TN levels (MPCA, 2013). As such, much of the discussion above about TN concentrations also applies here for NO_3 concentrations.

As the three major rivers entered the metro area, the Minnesota River had the highest 10-year median NO_3 concentration (2.94 mg/L at Jordan), the St. Croix River had the lowest NO_3 concentration (0.24 mg/L at Stillwater), and the Mississippi River had an intermediate concentration (0.93 mg/L at Anoka). The reasons for these marked differences in NO_3 concentrations between rivers are noted in the discussion of TN concentrations (above).

In a statewide study, the MPCA found that NO_3 concentrations and loads were high across much of southern Minnesota, mostly due to leaching from large areas of croplands into groundwater and tile drains (MPCA, 2013). The Cedar, Blue Earth, and Le Sueur watersheds, which are all in the Minnesota River Basin, exhibited the highest yields (amounts per acre) of nitrogen reaching surface waters. Statewide, croplands are the most common source of NO_3 (MPCA, 2013). With agriculture being the predominant land cover in the Minnesota River Basin (see "Study Area and Scope"), it follows that the Minnesota River would have higher NO_3 concentrations than the Mississippi and St. Croix rivers, where the percentage of agricultural land cover in the contributing watersheds is lower.

Figure 95. Median Nitrate-Nitrogen Concentrations (mg/L) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



The ratio of NO_3 concentration to TN concentration can also reflect differences between the three rivers. In the Minnesota River, the 10-year median NO_3 concentrations at the two monitoring sites were 69% and 66% of their respective 10-year median TN concentrations. In the St. Croix River, however, NO_3 concentrations were only 26% and 50% of their respective TN concentrations at Stillwater and Prescott. In the Mississippi River above the Minnesota River confluence, NO_3:TN median ratios were 54% and 43% at Anoka and Lock and Dam 1. TN in the Minnesota River was mainly in the form of NO_3, while NO_3 made up half or less of TN in the other two rivers. These results support the MPCA's findings, which showed that NO_3 was the main form of TN in streams and tributaries in agricultural areas, whereas organic nitrogen was the main form of TN in areas that have more natural land cover such as forests and wetlands (MPCA, 2013). Regardless, NO_3 is the most dominant form of nitrogen when TN is elevated (MPCA, 2013), and elevated TN is almost always a result of human activities, such as agriculture and wastewater treatment (Dubrovski et al., 2010).

In the metro area segment of the Mississippi River, the 10-year median NO_3 concentrations were lowest in the upstream portion of the river (Anoka and Lock and Dam 1), with a 29% decrease evident between the first two monitoring sites. As suggested in the TN discussion above, it is possible that conditions in Pool 1 (above Lock and Dam 1) were favorable for NO_3 loss via denitrification (conversion of NO_3 to atmospheric nitrogen). The high NO_3 concentration in the Minnesota River (3.02 mg/L at Fort Snelling) caused the median NO_3 concentration to increase 153% in the Mississippi River between Lock and Dam 1 (0.66 mg/L) and Saint Paul (1.67 mg/L). This Minnesota River impact influenced NO_3 concentrations in the entirety of Pool 2 in the Mississippi River, although the higher NO_3 concentrations at Grey Cloud Island and Lock and Dam 2 also reflected NO_3 contributions from the Metro WWTP. The lower NO_3 concentration in the St. Croix River (0.58 mg/L at Prescott) provided a dilution effect in the Mississippi River, causing NO_3 to decrease 20% between Lock and Dam 2 (2.02 mg/L) and Lock and Dam 3 (1.62 mg/L).

The median NO_3 concentration in the Minnesota River increased slightly as it passed through the metro area, with a 3% increase between Jordan and Fort Snelling. The discussion of TN concentrations in the lower Minnesota River (above) notes that NO_3 moves through this stretch of the river with little transformation (James 2007), and multiple NO_3 sources (tributaries, urban stormwater runoff, the Seneca and Blue Lake WWTPs, and the Xcel Energy Black Dog Generating Station) may account for the slight increase in NO_3 concentration between Jordan and Fort Snelling (MPCA, 1985). In Minnesota River tributaries, median annual flow-weighed mean concentrations of NO_3 ranged from 0.17-9.34 mg/L during the 2003-2012 period (MCES, 2014), with the highest concentrations present in those tributaries with predominantly agricultural land use in their watersheds. James (2007) determined that in low river flow conditions, the Seneca and Blue Lake WWTPs accounted for a majority of the net input of NO_3 within this stretch of the river. However, the Black Dog Generating Station acted as a net sink, retaining about 47% of the NO_3 input from the Minnesota River, due to denitrification within the pond system at the station.

In the St. Croix River, the median NO_3 concentration increased 142% between Stillwater and Prescott. Lafrancois et al. (2009) showed a similar result, with a notably higher median NOx (nitrate and nitrite) concentration evident at Prescott during the 1976-2004 period. Lafrancois et al. (2009) suggested that there are significant point and nonpoint sources contributing NOx to Lake St. Croix, such as WWTPs, tributaries, and nitrogen-rich groundwater. Of 12 major tributaries in the St. Croix River watershed, the two with the highest NO_3 concentrations during baseflow and the two with the highest percentages of agricultural land cover are the Kinnickinnic and Willow rivers (Lenz et al., 2003). These two tributaries drain directly into Lake St. Croix between the two monitoring sites.

The patterns of 10-year median NO_3 concentrations in the three metro area rivers were consistent with patterns of NO_3 concentrations in their tributaries. Flow-weighted median annual NO_3 concentrations in Minnesota River tributaries (2003-2012) were generally higher than those in Mississippi and St. Croix River tributaries (MCES, 2014), as was also the case for TSS and TP concentrations.

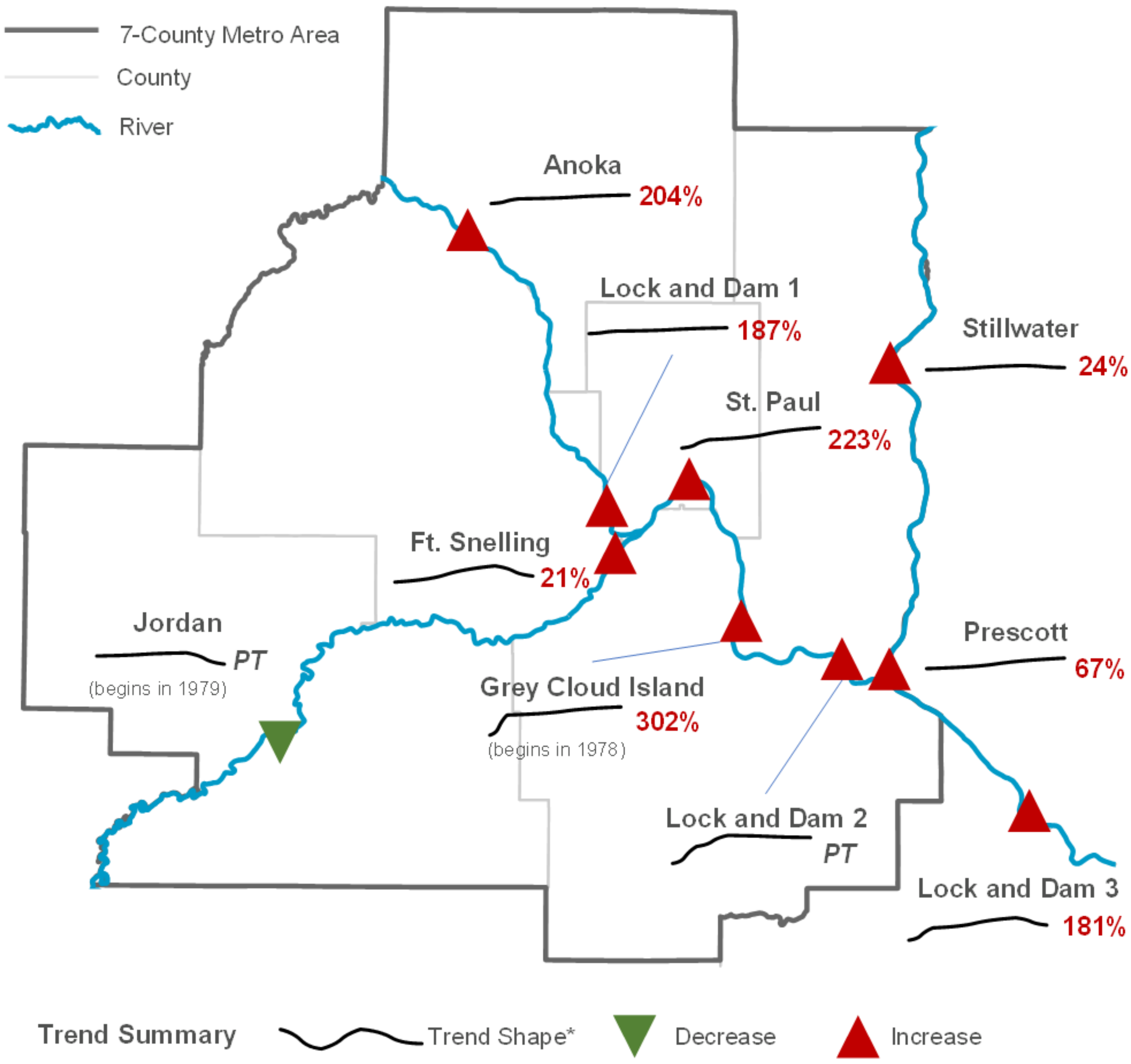
MCES WWTPs are point-source contributors of NO_3 to metro area rivers. During the 2006-2015 period, the median NO_3 concentration in Metro WWTP discharge was 14.6 mg/L, with the Metro WWTP contributing 3% of the median Mississippi River flow (MCES unpublished data accessed Dec. 2017). Similarly, the 10-year median NO_3 concentrations in the Blue Lake and Seneca WWTP discharges to the Minnesota River were 15.6 and 17.5 mg/L, respectively, with both WWTPs combining to contribute 2% of the median Minnesota River flow (MCES unpublished data accessed Dec. 2017). While the Metro WWTP NO_3 contribution resulted in a 16-21% increase in downstream Mississippi River NO_3 concentrations in Pool 2, NO_3 contributions from the Blue Lake and Seneca WWTPs had a smaller impact on the lower Minnesota River, being among multiple NO_3 contributions and river processes that resulted in a slight increase in NO_3 concentrations from Jordan to Fort Snelling.

Currently in Minnesota, the only water quality standard applied to NO_3 states that concentrations cannot exceed 10 mg/L in drinking water sources (Minn. Rules Chapter 7050). In the metro area, river reaches where this standard applies include the St. Croix River and the Mississippi River upstream from St. Anthony Falls. The 10-year median NO_3 concentrations at MCES monitoring sites within these river reaches were all substantially less than the 10 mg/L drinking water standard (Figure 95). NO_3 concentrations in the Mississippi River near the drinking water intakes for Minneapolis and Saint Paul were approximately 1 mg/L or less (MPCA, 2014). The MPCA is currently developing a standard for NO_3 in Minnesota's surface waters that will protect aquatic life.

40-Year Trends. Figure 96 displays overall trends in flow-adjusted NO_3 concentrations in the metro area Mississippi, Minnesota, and St. Croix rivers. Trend results show that, with the exception of the Minnesota River at Jordan, NO_3 concentrations have significantly increased across all three rivers during the last 40 years, indicating declining water quality.

At river entry points to the metro area, NO_3 concentration trends are mixed, with a 204% increase at the Mississippi River entry point (Anoka), a partial decrease at the Minnesota River entry point (Jordan), and a 24% increase at the St. Croix River entry point (Stillwater). Previous authors (Table 33 and Table 34) have also documented NO_3 concentration trends in metro area rivers at MCES monitoring sites. Although trend analysis methods and study periods differ, all authors concluded that NO_3 concentrations have increased at the Mississippi and St. Croix River entry points, at magnitudes similar to those noted in this report. Previous authors have observed a decreasing NO_3 concentration trend at the Minnesota River entry point, as is evident in this report.

Figure 96. Flow-Adjusted Nitrate-Nitrogen Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers, 1976-2015



Presented with overall percentage change, unless noted with the following:

PT – Partial Trend

One of the multiple trends within the assessment period is not statistically significant, so a representative percentage change could not be calculated

* Different scaling is applied to the lines of each site to visually emphasize the trend shapes. For accurate magnitudes of the trends, refer to the Results section of the report.

Table 33. Results from Past Studies on Nitrate-Nitrogen Concentration Trends in the Mississippi River

Author	Study Period	Trend Analysis Method	Anoka	Lock and Dam 1	Saint Paul	Grey Cloud Island	Lock and Dam 2	Lock and Dam 3
MCES, 2004	1976-2002	SEAKEN	31%					12%
Lafrancois, 2013	1976-2005	SEAKEN	49%	58%	NT	53%	47%	
MPCA, 2013	1976-2010	QWTREND	134%		149%	206%	172%	168%

SEAKEN: nonparametric Seasonal Kendall test; locally-weighted scatterplot smoothing (LOWESS) procedure used to remove effects of flow on concentration

NT: no significant trend

Table 34. Results from Past Studies on Nitrate-Nitrogen Concentration Trends in the Minnesota and St. Croix Rivers

Author	Study Period	Trend Analysis Method	Jordan	Fort Snelling	Stillwater	Prescott
MCES, 2004	1976-2002	SEAKEN	-20%		17%	
Johnson, 2009	1976-2003	QWTREND		64%		
Lafrancois, 2013	1976-2005	SEAKEN		NT		
MPCA, 2013	1976-2010	QWTREND	-26%	-6%	19%	74%

SEAKEN: nonparametric Seasonal Kendall test; locally-weighted scatterplot smoothing (LOWESS) procedure used to remove effects of flow on concentration

NT: no significant trend

The greatest increases in NO_3 concentrations occurred along the metro area Mississippi River, with the substantial increase at Anoka (204%) reflecting water quality deterioration in the upstream basin. This upstream increase in NO_3 concentrations seems to influence the entire metro area Mississippi River corridor, as similar increases in NO_3 concentrations, ranging from 187-302%, are evident downstream from Anoka. The greatest increase in NO_3 concentration (302%) occurred at Grey Cloud Island, downstream from the Metro WWTP. A more moderate increase in NO_3 concentration (181%) at Lock and Dam 3 might be attributed to dilution by the St. Croix River, where the NO_3 concentration and trend magnitude at Prescott are substantially less. Detailed sub-trends results (Table 40 through Table 45 (found in the "Appendix") show that the greatest increases in Mississippi River NO_3 concentrations occurred during the 1976-1984 period, with more moderate increases evident until 2015.

Using a different statistical method to assess metro area Mississippi River NO_3 concentration trends during the 1976-2005 period, Lafrancois et al. (2013) also noted increases in NOx concentrations (Table 33) through the Mississippi National River and Recreation Area, at the same monitoring sites used in this report. However, these increases were more moderate, ranging from 47%-58% at sites from Anoka to Lock and Dam 2. The 2016 State of the River Report (Weller and Russell 2016) noted that the average annual NO_3 concentration at Lock and Dam 2 increased by 44% during the 1976-2014 period. MCES (2004) found a 31% increase in NOx concentrations at Anoka and a 12% increase at Lock and Dam 3 during the 1976-2002 period (Table 33). The MPCA's (2013) analysis of NO_3 concentration trends in the metro area Mississippi River during the 1976-2010 period (Table 33) showed increases that are very similar to those noted in this report. The MPCA also used QWTREND for their analysis.

In the Minnesota River, NO_3 concentration trends are mixed, with a partial decreasing trend evident at Jordan, but a 21% increase observed at Fort Snelling. As noted above, multiple NO_3 sources (tributaries, urban stormwater runoff, the Seneca and Blue Lake WWTPs, and the Xcel Energy Black Dog Generating Station) may account for the increasing NO_3 concentration at Fort Snelling. However, sub-trend results (Table 46 and Table 47 in the "Appendix") show that NO_3 concentrations at Jordan and Fort Snelling have decreased by 28% and 22%, respectively, during the recent 2005-2015 period. Past studies of NO_3 concentration trends in the lower Minnesota River (Table 34) also show decreasing trends at Jordan (MCES, 2004; MPCA, 2013). At Fort Snelling, the results of past trend studies (Johnson, 2009; Lafrancois et al., 2013; MPCA, 2013) are mixed, with Johnson (2009) and MPCA (2013) using QWTREND as the statistical tool for trend analysis. However, the most recent analysis, conducted by the MPCA (2013), shows a 6% decrease in the NO_3 concentration at Fort Snelling during the 1976-2010 period.

In the St. Croix River, NO_3 concentrations at Stillwater and Prescott increased by 24% and 67%, respectively. The sub-trend results (Table 48 and Table 49 in the "Appendix") indicate that the NO_3 concentration at Stillwater gradually increased from 1976 to 2003, then decreased from 2004 to 2015. The NO_3 concentration at Prescott has continuously increased over the entire assessment period (1976 to 2015). Lafrancois et al. (2009) noted significant NO_x concentration increases at Stillwater and Prescott during the 1976-2004 period. Although the overall magnitudes of those trends were not determined, the rates of change in NO_x concentrations were 0.0050 and 0.0051 mg/L/year at Stillwater and Prescott, respectively

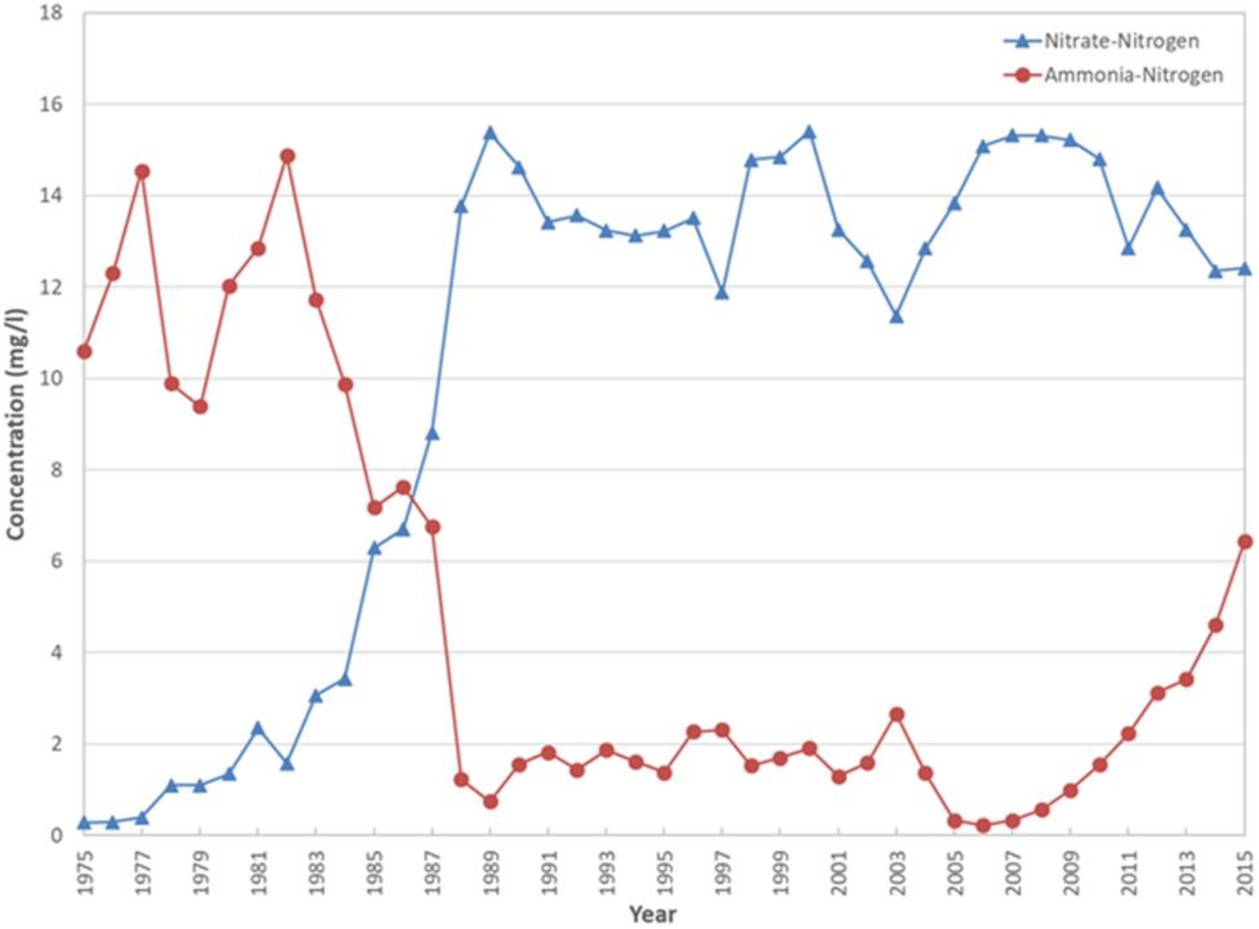
Due to the concern about aquatic toxicity caused by high concentrations of NH_3 in MCES WWTP discharges to metro area rivers, advanced secondary treatment was implemented at the Metro, Blue Lake, and Seneca WWTPs, beginning in 1984. Advanced secondary treatment has substantially reduced NH_3 concentrations in MCES WWTP discharges, via a biological nitrification process that converts NH_3 to NO_3. Results of the application of advanced secondary treatment at the Metro WWTP are shown in Figure 97. Trend analysis by Lafrancois et al. (2013) showed that advanced secondary treatment at the Metro WWTP reduced the NH_3 concentration by 679% during the 1976-2005 period; however, the NOx concentration increased by 114%.

According to the MPCA's state-wide nitrogen study (MPCA, 2013), nitrogen sources contributing to Minnesota's waters include cropland tile drainage (37%), groundwater (30%), atmospheric deposition (9%), point sources (9%), forests (7%), agricultural runoff (5%), and septic systems (2%). Increasing NO_3 concentrations in regional rivers may be potentially linked to (1) changes in land management, agriculture practices, and climate; (2) increasing usage of fertilizers on agricultural croplands and urban lawns; (3) expansion of livestock and poultry production; and (4) increasing population. Although NO_3 concentrations have been decreasing at some metro area river sites in recent years, excessive nitrogen concentrations in surface waters are a major statewide concern.

The Minnesota Nutrient Reduction Strategy (MPCA 2014) provides guidance for reducing excess nutrients in state waters, so that in-state and downstream water quality goals are ultimately met. For nitrogen in the Mississippi River Major Basin (including the Minnesota and St. Croix river watersheds), a milestone reduction of 20% has been established, with a target date of 2025. Recommendations for meeting this milestone include reducing nitrogen contributions from both point and nonpoint sources. Progress toward nitrogen reductions at WWTPs has already been achieved by reducing NH_3 concentrations. Further nitrogen reduction could come via reductions in NO_3 concentrations. Nonpoint source reductions can be achieved by increasing fertilizer-use efficiencies, increasing and targeting living cover, and retaining drainage water for treatment. The sharp seasonal peaks in NO_3 concentrations observed in June in the Mississippi River (Figure 29 in "Results") and Minnesota River

(Figure 48 in “Results”), particularly in the last two decades, suggest that there may be options to address the timing and/or magnitude of agricultural nitrogen applications to reduce NO_3 contributions. Continuing long-term monitoring and data analysis are needed to determine whether NO_3 concentrations decrease as a result of state-wide and regional nitrogen reduction programs.

Figure 97. Annual Mean Nitrate-Nitrogen and Ammonia-Nitrogen Concentrations in Metro Wastewater Treatment Plant Discharge, 1975-2015



Ammonia-Nitrogen (NH_3)

NH_3 exists as two forms in aquatic environments: un-ionized ammonia and ammonium (MPCA, 2013). NH_3 is formed when organic matter decomposes, and NH_3 can be transformed into other forms of nitrogen, such as NO_2 and NO_3. Un-ionized ammonia is toxic to aquatic life, whereas ammonium is relatively less toxic and more common in most Minnesota's surface waters (MPCA, 2013). However, as pH and temperature increase, ammonium can convert into the more toxic un-ionized form. In this report, NH_3 refers to the sum of un-ionized ammonia and ammonium.

Sources of NH_3 to Minnesota's surface waters include human and animal waste (for example, municipal WWTPs, leaking septic systems, and feedlots), some fertilizers, and industrial waste (MPCA, 2013). Natural sources of NH_3 include the decomposition of organic matter containing nitrogen (for example, protein and nucleic acid), gas exchange with the atmosphere, and forest fires. The most common pathways of NH_3 into water are through runoff and discharges from point sources. NH_3 in surface waters can have a directly toxic effect on fish and other aquatic life, and it can also cause significant oxygen depletion when nitrification occurs.

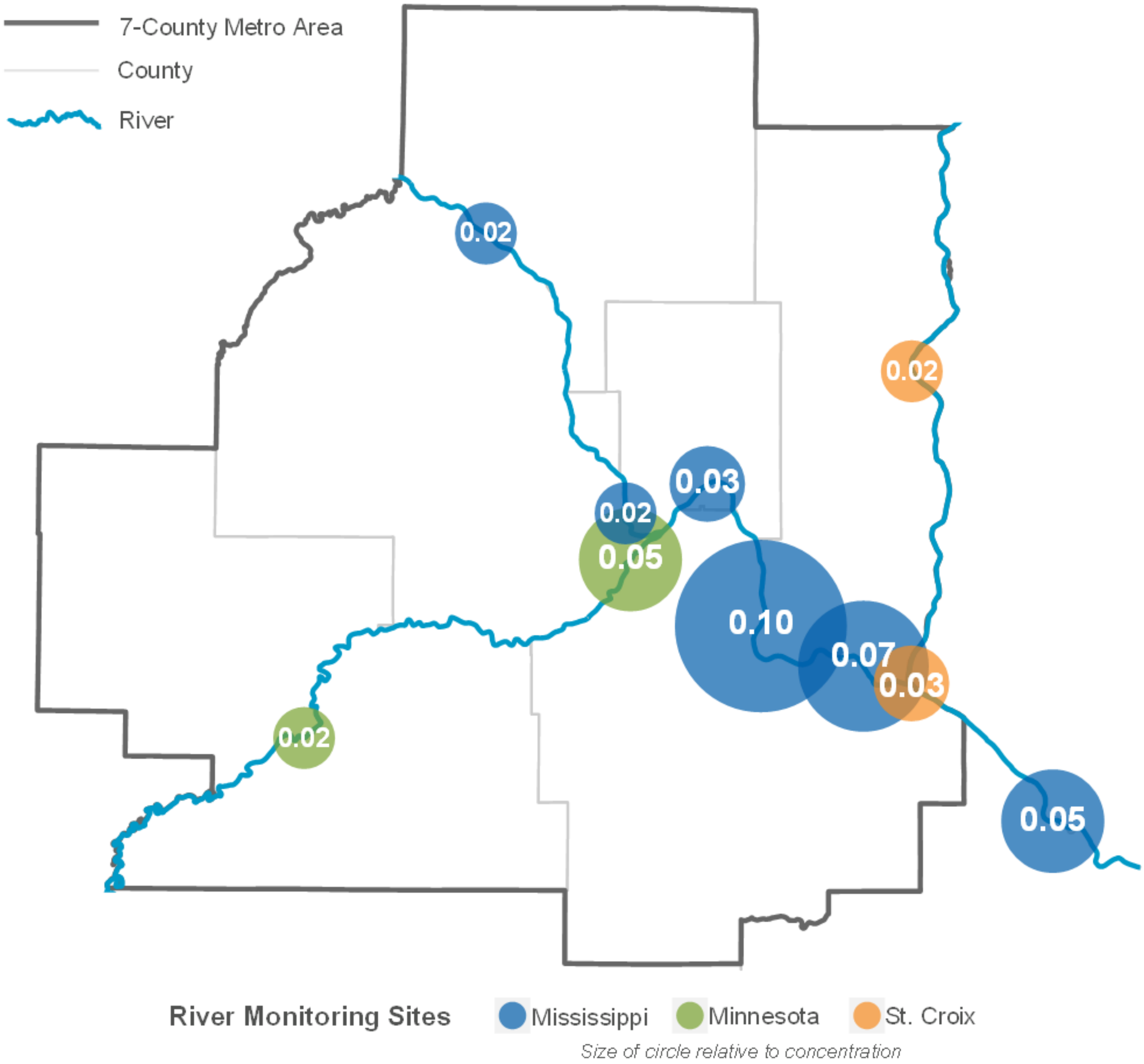
Recent Conditions. Figure 98 displays the median NH_3 concentrations measured from 2006-2015 at each of the river monitoring sites in the metro area. As the three major rivers entered the metro area, they all had the same low 10-year median NH_3 concentration of 0.02 mg/L. This concentration is also the lower (reporting) limit for analysis of NH_3 samples in the MCES laboratory (Table 6 in "Study Methods"). For the purpose of this analysis, all NH_3 results reported as less than 0.02 mg/L were assigned values of 0.02 mg/L. As a result, the true 10-year median NH_3 concentrations are likely lower than those displayed in Figure 98, especially as these values approach the lower limit (0.02 mg/L).

NH_3 is often converted into NO_2 and NO_3 through nitrification in rivers and streams, except in the winter (MPCA, 2013). As such, NH_3 concentrations in metro area rivers typically reflect local pollution sources, since NH_3 from more remote sources has already likely been transformed via nitrification. The low NH_3 concentrations in the rivers as they entered the metro area were likely not an indication that there are no sources of excess NH_3 upstream, but that NH_3 was converted before reaching the metro area. In fact, NH_3 concentrations are generally less than 0.1 mg/L in surface waters across much of the state, except for specific locations such as the metro area (MPCA, 2013).

In the metro area of the Mississippi River, the 10-year median NH_3 concentrations were lowest in the upstream river reach from Anoka to Lock and Dam 1 (0.02 mg/L). The higher NH_3 concentration in the Minnesota River (0.05 mg/L at Fort Snelling) caused the NH_3 concentration to increase slightly in the Mississippi River between Lock and Dam 1 (0.02 mg/L) and Saint Paul (0.03 mg/L). The higher NH_3 concentrations at Grey Cloud Island (0.10 mg/L) and Lock and Dam 2 (0.07 mg/L) reflect NH_3 contributions from the Metro WWTP. The lower NH_3 concentration in the St. Croix River (0.03 mg/L at Prescott) provided a dilution effect in the Mississippi River, causing NH_3 to decrease between Lock and Dam 2 (0.07 mg/L) and Lock and Dam 3 (0.05 mg/L).

Wastewater is one of the most common sources of NH_3 to surface waters (MPCA, 2013), and the Metro WWTP is the largest municipal wastewater treatment facility in the state. Although advanced secondary treatment at the Metro WWTP has greatly reduced NH_3 concentrations in the treated wastewater since 1984 (Figure 97), the recent 10-year median NH_3 concentration in the Metro WWTP discharge was 1.2 mg/L (MCES unpublished data accessed Dec. 2017).

Figure 98. Median Ammonia-Nitrogen Concentrations (mg/L) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



In the Minnesota River, the NH_3 concentration increased from 0.02 mg/L at Jordan to 0.05 mg/L at Fort Snelling, as the river passed through the metro area. Several point sources likely contributed to this slight increase, including the Blue Lake and Seneca WWTPs. The 10-year median NH_3 concentrations in the Blue Lake and Seneca WWTP discharges were 0.13 and 0.09 mg/L, respectively (MCES unpublished data accessed Dec. 2017). However, the overall impact of these two WWTPs, compared to that from other sources of NH_3, depends on river flow conditions. MCES WWTP contributions are generally lower during high flows and higher in low flows (MPCA, 2013). For example, in the low flow period of 2006, the Seneca and Blue Lake WWTPs contributed 34% of the NH_3 load in the lower 40-miles of the Minnesota River, despite contributing only 5% of the overall flow (James, 2007; MCES, 2010). Xcel Energy's Black Dog Generating Station is also a net source of NH_3 in low flow conditions, possibly due to decomposition of organic matter in the pond system of the facility (James, 2007).

These known point sources do not account for all of the NH_3 present in the lower Minnesota River. During the 2004-2007 period, for example, the lower Minnesota River was a net source of NH_3, exporting 27% to 50% more NH_3 than received in the same stretch of the river (James, 2007; MCES, 2010). It has been suggested that this excess NH_3 originates from the senescence of algae and decomposition of organic matter in the lower Minnesota River (James, 2007; MCES, 2010). As previously noted in the discussion of Chl-*a* concentrations, the highest 10-year median Chl-*a* concentration in the three metro area rivers occurred at Jordan (0.043 mg/L). This decomposition of algae and organic matter in the lower Minnesota River also contributed to the increase in the 10-year median NH_3 concentration as the river moves through the metro area.

In the St. Croix River, the NH_3 concentration increased slightly between Stillwater (0.02 mg/L) and Prescott (0.03 mg/L). The MCES St. Croix Valley WWTP and the City of Hudson WWTP are minor point sources contributing NH_3 to Lake St. Croix. NH_3 entering the lake from other sources is likely converted to NO_3.

To protect aquatic life, the Minnesota water quality standard limits un-ionized ammonia to 0.04 mg/L as a 30-day average concentration in the state’s surface waters, including metro area rivers (Minn. Rules Chapter 7050). The amount of ammonia in the un-ionized form is calculated using the NH_3 concentration, temperature, and pH. As of 2016, there were no NH_3-related impairments in the metro area Mississippi, Minnesota, and St. Croix rivers (MPCA, 2016a).

40-Year Trends. Figure 99 displays overall trends in flow-adjusted NH_3 concentrations in the metro area Mississippi, Minnesota, and St. Croix rivers. During the trend assessment period (1976-2015), more than 10% of the measured NH_3 concentrations at each monitoring site (except Grey Cloud Island) were less than the analytical RL. In this circumstance, QWTREND results can only be used for exploratory analysis to understand trend directions. As such, no trend magnitudes were reported, except for an 82% decrease at Grey Cloud Island. Trend directions show that NH_3 concentrations have decreased across all three rivers during the last 40 years, indicating an improvement in water quality.

Previous reports by other authors (Table 35) have also documented decreasing NH_3 concentrations in metro area rivers at MCES monitoring sites. NH_3 concentrations along the Mississippi River corridor from Anoka to Lock and Dam 2 decreased by 214-353% during the 1976-2005 period (Lafrancois et al. 2013), and the NH_3 concentration at Lock and Dam 3 decreased by 91% during the 1976-2002 period (MCES, 2004). In the Minnesota River, NH_3 concentrations decreased by 72% at Jordan (MCES, 2004) and 221% at Fort Snelling (Lafrancois et al. 2013). In the St. Croix River, the NH_3 concentration decreased by 81% at Stillwater (MCES, 2004). As previously noted in the discussion of NO_3 concentrations, advanced secondary treatment has substantially reduced NH_3 concentrations in MCES WWTP discharges since 1984 (Figure 97), including a 679% reduction at the Metro WWTP (Lafrancois et al., 2013).

Figure 99. Flow-Adjusted Ammonia-Nitrogen Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers, 1976-2015

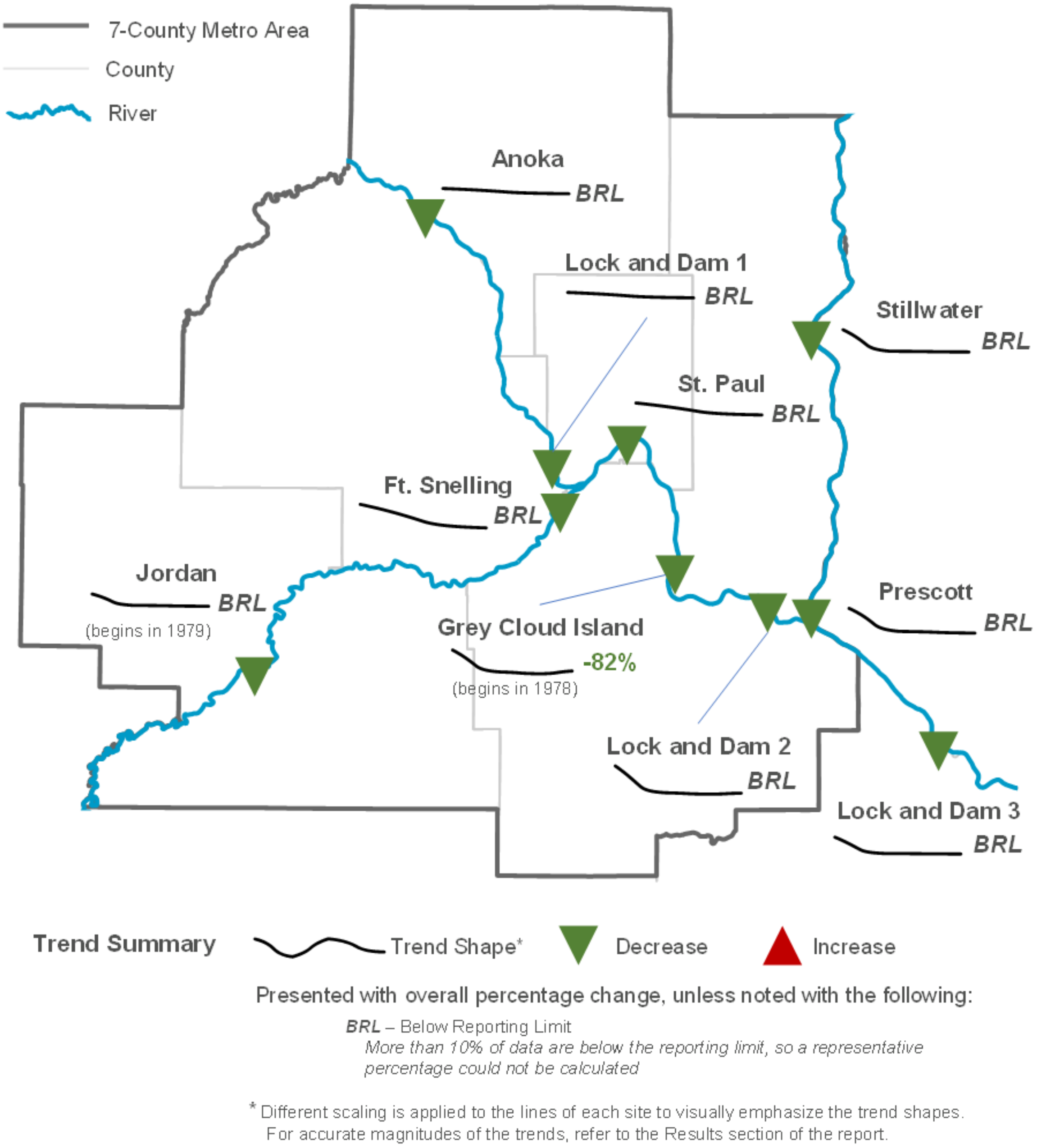


Table 35. Results from Past Studies on Ammonia-Nitrogen Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers

Author	Study Period	Trend Analysis Method	Anoka	Lock and Dam 1	Saint Paul	Grey Cloud Island	Lock and Dam 2	Lock and Dam 3	Jordan	Fort Snelling	Stillwater
MCES, 2004	1976-2002	SEAKEN	-78%*					-91%*	-72%*		-81%*
Lafrancois, 2013	1976-2005	SEAKEN	-214%	-234%	-230%*	-284%*	-353%**			-221%*	

SEAKEN: nonparametric Seasonal Kendall test

* Locally-weighted scatterplot smoothing (LOWESS) procedure used to remove effects of flow on concentration

Decreasing trends in NH_3 ammonia concentrations across the three metro area rivers, documented in this report and others, are an important indicator of progress for improving regional river water quality. The trend results show that decreases in NH_3 concentrations generally occurred after advanced secondary treatment was implemented at MCES WWTPs. The greatest benefits of those investments have been evident at the Grey Cloud Island and Lock and Dam 2 sites downstream from the Metro WWTP, where NH_3 concentrations decreased by 284% and 353%, respectively (Lafrancois et al. 2013). Similarly, NH_3 concentrations decreased by 221% at Fort Snelling, downstream from the Blue Lake and Seneca WWTPs (Lafrancois et al. 2013).

Fecal Coliform Bacteria (FC)

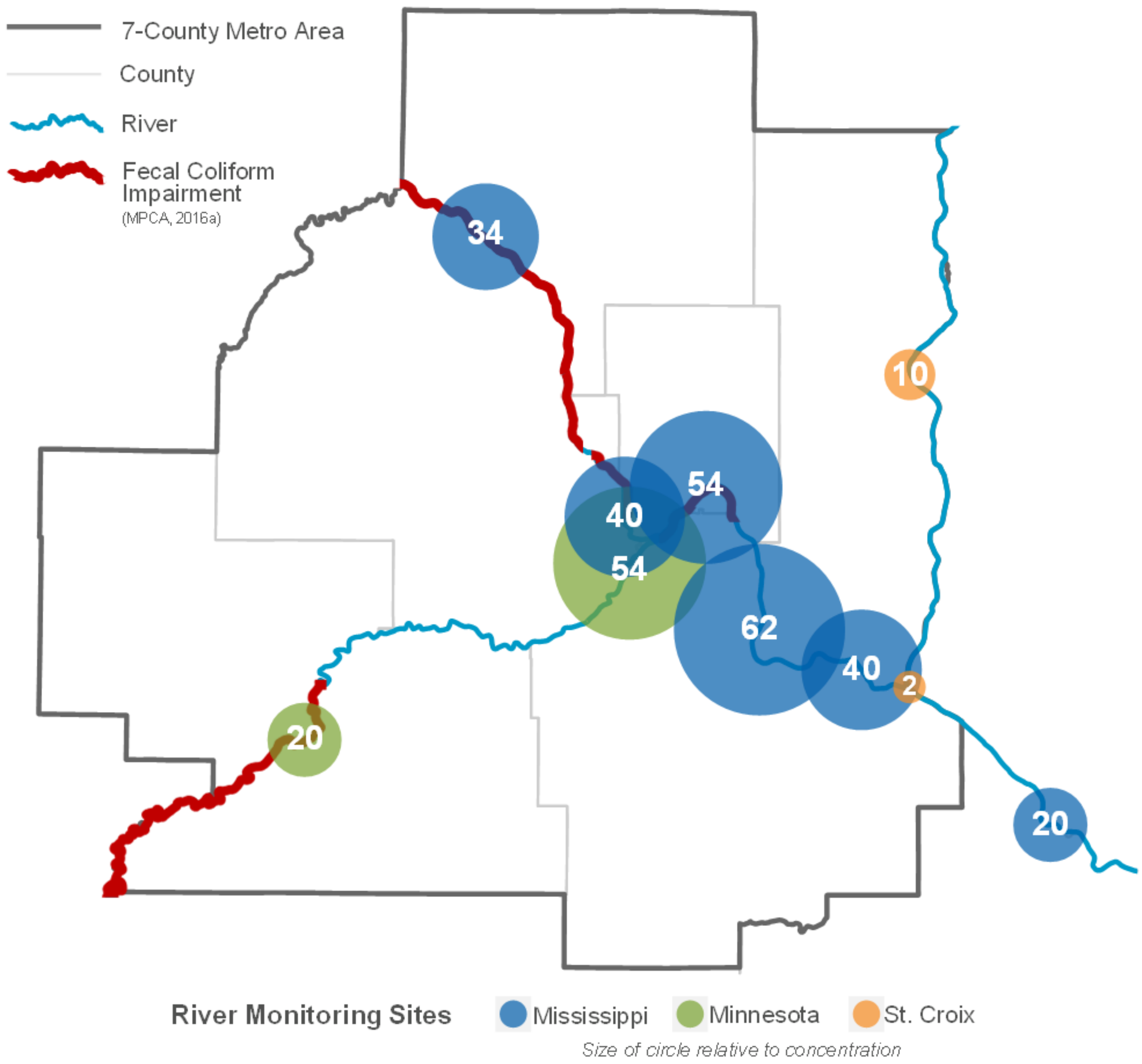
FC are mostly harmless bacteria which typically originate from human, pet, livestock, and wildlife waste, so their presence is usually an indication of fecal contamination in water (MPCA, 2008a). Fecal contamination can also introduce harmful pathogens into the water, which can cause illness to anyone exposed to them. Therefore, FC has historically been monitored as a general indicator, to determine if a waterbody is unsafe for recreational use due to bacterial contamination (USEPA, 2012g). However, some types of FC do not originate from fecal sources, which can reduce its usefulness as an indicator of fecal contamination (Francy et al., 1993).

Research has shown that *E. coli* bacteria are a better predictor of gastrointestinal illness due to bacterial contamination in freshwater environments (Dufour, 1984). As a result, in 1986 the EPA recommended that *E. coli* be monitored instead of FC to determine if a waterbody is unsafe for recreational use due to contamination (USEPA, 1986). However, due to the lengthy historical record of FC data, MCES has continued to monitor FC alongside *E. coli*, to use for long-term analysis. Also, NPDES permit limits for bacteria levels in MCES WWTP discharges continue to be based on FC bacteria, making it useful to continue monitoring FC concentrations in the metro area rivers affected by these discharges. MCES WWTP permit limits for FC only apply during the recreational season (April-October).

Recent Conditions. Figure 100 displays the median FC concentrations measured from 2006-2015 at each of the river monitoring sites in the metro area. As the three major rivers entered the metro area, the Mississippi River had the highest 10-year median FC concentration (34 organisms/100 mL at Anoka), the St. Croix River had the lowest concentration (10 organisms/100 mL at Stillwater), and the Minnesota River had an intermediate concentration (20 organisms/100 mL at Jordan).

The sources and transport of bacteria in a river and its watershed are varied and complex (EOR, 2014). Common sources of FC in rivers include WWTPs, leaking septic systems, overflowing sewers, runoff contaminated with pet and wildlife waste, runoff from animal feedlots, and runoff from land that has had manure applications (EOR, 2009a; 2014; MPCA, 2008a). In an extensive literature review, EOR (2009b) found that the most commonly mentioned conditions associated with high bacteria levels were large storm flows, more rural/agricultural land than forests in a watershed, more urban land than forests in riparian areas, high water temperatures, high percentages of impervious surfaces, livestock near waterbodies, and elevated concentration of suspended solids. As a result, FC levels tend to be lower in northern Minnesota, where forests and wetlands are abundant, and higher in areas of the state that have more agriculture or are more populated (MPCA, 2008a).

Figure 100. Median Fecal Coliform Concentrations (#/100mL) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



As noted in Figure 100, the Upper Mississippi River has been listed by the MPCA (2016a) as impaired due to excessive levels of FC bacteria. This FC impairment extends along the entire Mississippi River from Sartell to Saint Paul and includes the metro area reach from Anoka to Saint Paul. With the FC impairment in this river reach first identified by the MPCA in 2002, TMDL study and implementation plans have been developed to address this problem (EOR, 2014; MPCA, 2016c). The existing FC impairment in the Upper Mississippi River helps explain why the median FC concentration was highest at the Mississippi River's metro area entry point (Anoka), compared to FC concentrations at the Minnesota River and St. Croix River entry points (Jordan and Stillwater, respectively) (Figure 100).

The TMDL plan for the Upper Mississippi River FC impairment (EOR, 2014) identifies contributing FC sources, which include humans, livestock, pets, wildlife, urban stormwater, and river sediments. FC sources related to urban stormwater and WWTPs are particularly prevalent along the metro area Mississippi River corridor. The FC concentration at the Minnesota River entry point (Jordan) was not as high as that at the Mississippi River entry point (Anoka); however, the Minnesota River at Jordan is also listed as impaired due to excessive levels of FC bacteria. The Minnesota River watershed upstream of the metro area is more agricultural, while the Mississippi River watershed upstream from the metro area is slightly more developed (see “Study Area and Scope”). Both upstream watersheds have a substantial number of registered feedlots (8,712 and 9,520 in the Upper Mississippi River and Minnesota River watersheds, respectively) (MPCA, 2016b) and municipal WWTPs (187 and 156 in the Upper Mississippi River and Minnesota River watersheds, respectively) (MPCA, 2015c).

Both watersheds have common factors associated with bacteria contamination, and there are likely more FC sources than these livestock and human sources listed above. The relatively low FC concentration at the St. Croix River entry point (Stillwater) can likely be attributed to higher proportions of forest and wetland land cover in the upper watershed, with much smaller proportions of agriculture and developed land cover (see “Study Area and Scope”).

In the metro area of the Mississippi River, the highest 10-year median FC concentrations were evident near the central urban areas of Minneapolis and Saint Paul (40 organisms/100 mL and 54 organisms/100 mL at Lock and Dam 1 and Saint Paul, respectively), and downstream from the Metro WWTP (62 organisms/100 mL at Grey Cloud Island). As discussed previously, urban areas can be a significant source of bacteria, and pets, wildlife, and humans tend to be the main contributors of bacteria in these areas, often via stormwater and wastewater treatment-related inputs. During the April-October period, the Metro WWTP disinfects its treated wastewater discharge to the river, as required to meet the NPDES discharge limit for FC bacteria (200 organisms/100 mL). This limit is in place during the recreational season, when the water quality standard applies to protect human health. During the November-March (winter) period when the Metro WWTP permit limit does not apply, no disinfection occurs, and higher FC concentrations are being discharged to the river.

Since the 10-year median FC concentrations are calculated using data that are collected year-round at each site, the highest FC concentration at Grey Cloud Island includes data from winter periods each year when the Metro WWTP is not disinfecting its discharge. Upstream stormwater sources may also be contributing to the elevated FC concentration at Grey Cloud Island. As the Mississippi River continued through Pool 2, the FC concentration decreased to 40 organisms/100 mL at Lock and Dam 2. While it’s difficult to identify the cause of this decrease, an MPCA literature review found that factors commonly contributing to bacteria declines in surface waters include deactivation from sunlight (UV-A), sedimentation, and temperature (EOR, 2009a). The very low FC concentration in the St. Croix River (2 organisms/100 mL at Prescott) provided a dilution effect in the Mississippi River, causing FC to decrease 50% between Lock and Dam 2 (40 organisms/100 mL) and Lock and Dam 3 (20 organisms/100 mL).

The FC concentration in the Minnesota River increased by 170% from Jordan (20 organisms/100 mL) to Fort Snelling (54 organisms/100 mL). This increase was likely due to a combination of contributing sources, including feedlots, agricultural lands, stormwater inputs via tributary streams, and the Blue Lake and Seneca WWTPs. As at the Metro WWTP, no disinfection of the Blue Lake and Seneca WWTP discharges occurs during the November-March period each year. As a result, higher FC concentrations in these discharges during the winter were contributing to the increased FC concentration at Fort Snelling.

In the St. Croix River, the FC concentration decreased by 80% between Stillwater (10 organisms/100 mL) and Prescott (2 organisms/100 mL). The MCES St. Croix Valley WWTP and the City of Hudson WWTP are minor point sources that seasonally contribute FC to Lake St. Croix. However, the St. Croix River watershed has less development and agricultural land, both of which can serve as significant sources of FC bacteria (MPCA, 2008a). As discussed previously, temperature, sedimentation, and deactivation from sunlight all serve as mechanisms that can reduce bacteria levels (EOR, 2009a).

In 2008, the Minnesota state standard for FC bacteria in surface waters was replaced with a standard for *E. coli* bacteria. This change was prompted by an EPA recommendation (USEPA, 1986). After 2008, the MPCA monitored both parameters simultaneously for several years, and found that *E. coli* is generally a more stringent indicator of fecal contamination (MPCA, 2008b). Due to the historical use of FC bacteria as an indicator of fecal contamination, many impairments for FC still exist. As shown in Figure 100, sites on metro area river reaches that have been designated by the MPCA as impaired by excessive levels of FC bacteria include the Mississippi River at Anoka, Lock and Dam 1, and Saint Paul, as well as the Minnesota River at Jordan (MPCA, 2016a).

40-Year Trends. Figure 101 displays overall trends in flow-adjusted FC concentrations in the metro area Mississippi, Minnesota, and St. Croix rivers. Similar to the decreasing trends noted for BOD_5, TSS, TP, and NH_3 concentrations in regional rivers, FC concentrations have also decreased significantly in the rivers during the last 40 years, indicating an improvement in water quality.

At river entry points to the metro area, FC concentrations have decreased by 66% at Anoka, 88% at Jordan, and 59% at Stillwater. MCES (2004) also analyzed FC concentration trends at river entry points during the 1976-2002 period (Table 36). Although no trend was apparent at Anoka, decreases in FC concentrations at Jordan (-71%) and Stillwater (-64%) were very similar to those noted in this report.

Downstream from the Mississippi River entry point at Anoka, the greatest decreases in FC concentrations occurred at Saint Paul (-96%) and Grey Cloud Island (-98%). At Lock and Dam 1, a partial decreasing trend was noted during the 1976-2010 period, with no recent trend apparent during the 2011-2015 period. At Lock and Dam 2 and Lock and Dam 3, FC concentrations decreased by 67% and 77%, respectively. MCES (2004) found a similar 71% decrease at Lock and Dam 3 (Table 36).

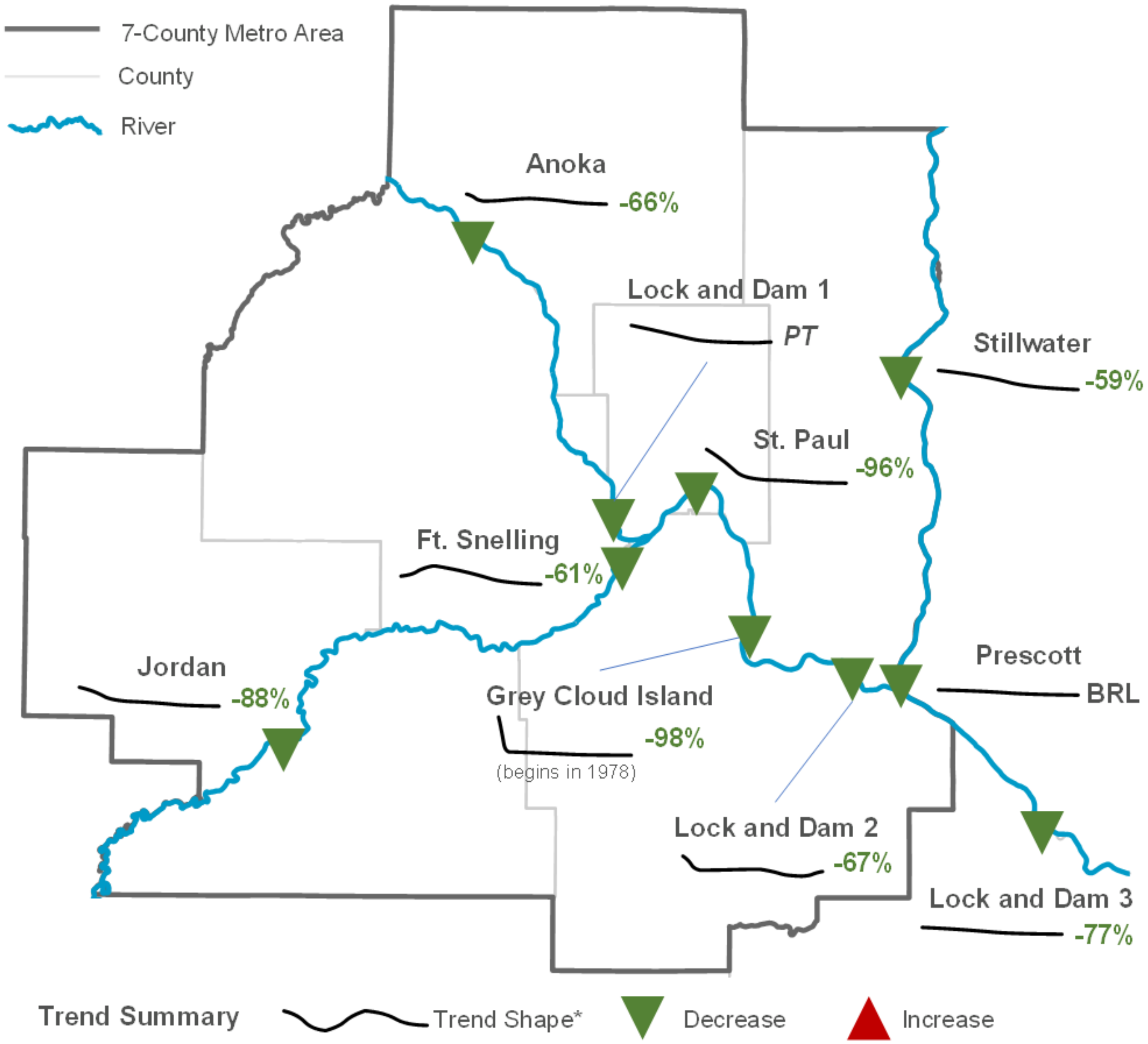
In the Minnesota River, a greater decrease in FC concentration occurred upstream at Jordan (-88%), compared to the downstream decrease at Fort Snelling (-61%).

In the St. Croix River, a significant decreasing trend in FC concentration was apparent at Prescott. However, the magnitude of this trend could not be quantified, as more than 10% of the FC analyses were less than the RL. As noted above, the FC concentration at Stillwater decreased by 59%.

The significant decreases in FC concentrations at all metro area river monitoring sites reflect improving water quality, likely due to decreasing FC inputs from multiple sources in the upstream watersheds and within the metro area.

During the 1985-1995 period, the cities of Minneapolis, Saint Paul, and South Saint Paul invested $331 million to separate combined sewer overflow (CSO) systems that were discharging untreated sewage (including FC bacteria) to the Mississippi River during rain events. After CSO separation was complete, all untreated sewage was directed to the Metro WWTP for appropriate treatment, including disinfection of FC bacteria. In 1984, 77 CSO events in Minneapolis and Saint Paul contributed over a billion gallons of untreated wastewater and stormwater to the Mississippi River. In 2007, no CSO events occurred, with no untreated wastewater and stormwater discharged to the river (EOR 2009a). The success of the CSO separation program is reflected in the substantial decreases in FC concentrations (67-98%) at Mississippi River monitoring sites in Pool 2, from Saint Paul to Lock and Dam 2.

Figure 101. Flow-Adjusted Fecal Coliform Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers, 1976-2015



Presented with overall percentage change, unless noted with the following:

BRL – Below Reporting Limit
More than 10% of data are below the reporting limit, so a representative percentage could not be calculated

PT – Partial Trend
One of the multiple trends within the assessment period is not statistically significant, so a representative percentage change could not be calculated

* Different scaling is applied to the lines of each site to visually emphasize the trend shapes. For accurate magnitudes of the trends, refer to the Results section of the report.

Table 36. Results from Past Studies on Fecal Coliform Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers

Author	Study Period	Trend Analysis Method	Anoka	Lock and Dam 3	Jordan	Stillwater
MCES, 2004	1976-2002	SEAKEN	NT	-71%	-71%	-64%

SEAKEN: nonparametric Seasonal Kendall test; locally-weighted scatterplot smoothing (LOWESS) procedure used to remove effects of flow on concentration

NT: no significant trend

In addition to human sources of FC bacteria in untreated sewage, pets, wildlife, and waterfowl are major contributors of FC bacteria in urban and suburban areas (MPCA, 2016c). In 2002, the MPCA issued a general permit for MS4s discharging stormwater to Minnesota’s surface waters. This permit requires cities with MS4s in urban areas to implement practices that reduce pollutants in stormwater, including FC bacteria.

Important components of the MS4 general permit that are beneficial for reducing FC sources include: (1) detecting and eliminating illicit connections to the storm sewer system (such as wastewater connections); (2) construction site runoff controls; (3) post-construction runoff controls; and (4) good housekeeping practices such as street sweeping and ordinances requiring clean-up of pet wastes. Weller and Russell (2016) also note that the Mississippi River may be “inheriting” some of its elevated bacteria concentrations from its tributaries. Implementation of MS4 stormwater management practices by metro area cities has likely led to FC reductions in these tributary contributions to the major rivers.

Decreasing FC concentrations in metro area rivers may also reflect overall water quality improvements due to upstream, basin-wide water pollution programs. The Upper Mississippi River Bacteria TMDL Project (EOR, 2014; MPCA, 2009d) has been targeting the implementation of best management practices (BMPs) that reduce surface runoff and improve the management of feedlots, manure, and septic and sewage systems.

Although previous and current study results indicate that FC concentrations have significantly decreased in the three metro area rivers, FC concentrations in portions of the Mississippi and Minnesota rivers are still a major regional water quality concern (MPCA, 2016a), resulting in water quality impairments (Figure 100). Weller and Russell (2016) indicated that some stretches of the metro Mississippi River have been identified as having too much fecal bacteria since 1996. As noted above, TMDL studies and implementation plans have been developed to address this problem (EOR 2014, MPCA 2016c). The MCES river monitoring program will continue collecting and analyzing FC bacteria data to help assess ongoing sources of FC bacteria and evaluate the progress of the TMDL implementation plan.

Escherichia coli Bacteria (*E. coli*)

E. coli bacteria, like FC bacteria, are monitored to indicate the potential presence of harmful pathogens in water (MPCA, 2008a). *E. coli* and FC bacteria are almost always found simultaneously in water (MPCA, 2008a). As with FC, *E. coli* typically originates from human, pet, livestock, and wildlife waste, reaching rivers from WWTPs, leaking septic systems, overflowing sewers, runoff contaminated with pet and wildlife waste, runoff from animal feedlots, and runoff from land with manure applications (EOR, 2009a; 2014; MPCA, 2008a). In 1986, the EPA recommended that *E. coli* be monitored instead of FC to test for the possible presence of harmful pathogens (USEPA ,1986), in part because *E. coli* was found to be a better predicator of gastrointestinal illness due to bacterial contamination in freshwater environments (Dufour, 1984).

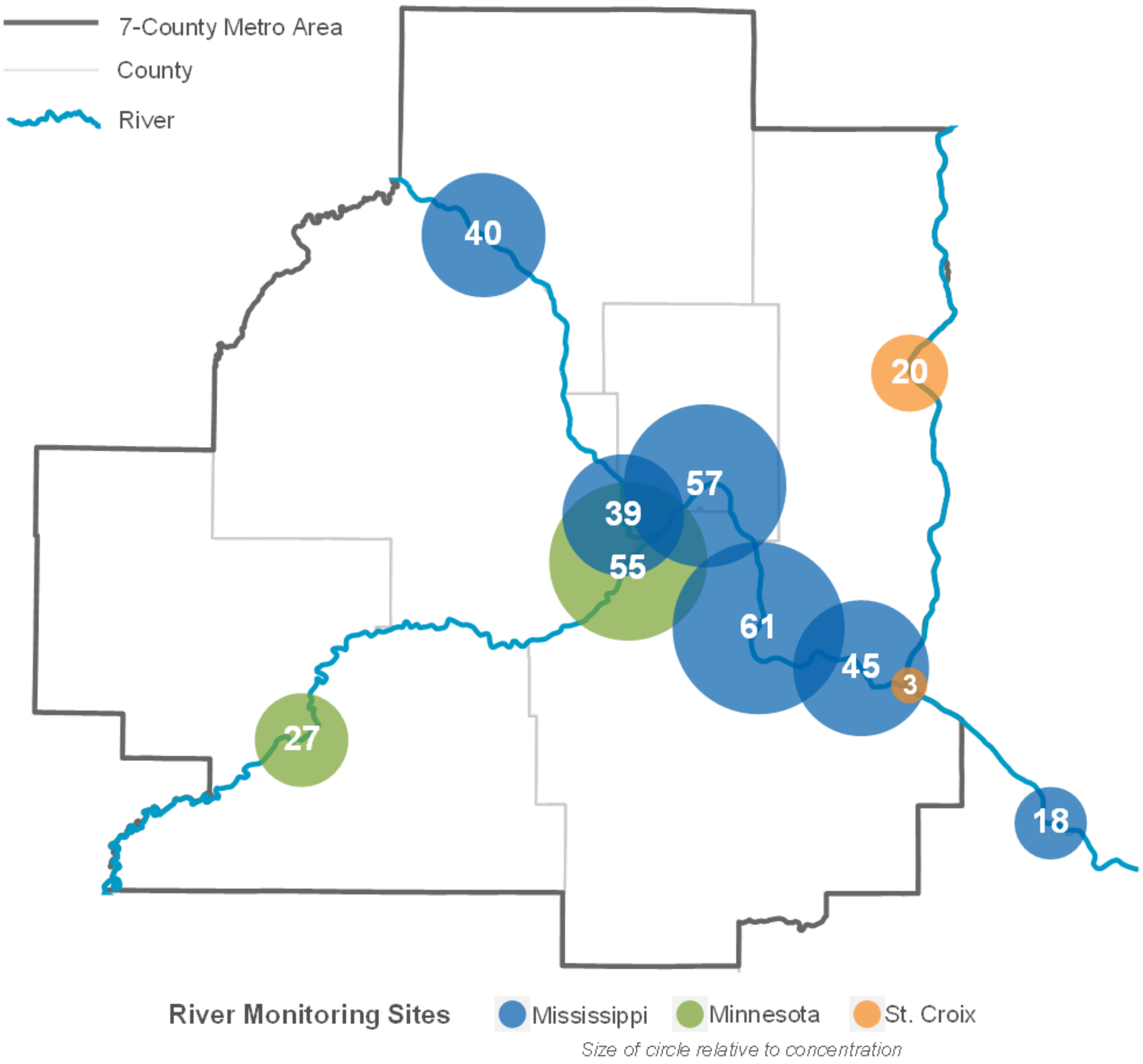
Recently, however, there has been some doubt about the usefulness of *E. coli* as an indicator of contamination (EOR, 2009b). In some cases, harmful pathogens exist in the absence of *E. coli* (for example, Bushon and Kolton, 2004). Also, challenges associated with sampling and analyzing bacteria can sometimes create significant uncertainty in the *E. coli* results (McCarthy et al., 2008; USEPA, 2012g). Additionally, *E. coli* has been found in the environment independent from sources of fecal contamination (for example, Byappanahalli et al. 2006, Ishii et al. 2006), thereby potentially reducing the usefulness of *E. coli* as an indicator of harmful pathogens (EOR, 2009a). Regardless of these caveats, under most conditions, higher concentrations of *E. coli* correlate with higher concentrations of other harmful pathogens in water (EOR, 2009b).

Recent Conditions. Figure 102 displays median *E. coli* concentrations measured from 2006-2015 at each of the river monitoring sites in the metro area. *E. coli* concentrations and patterns across the three metro area rivers are nearly identical to those observed for FC concentrations (Figure 100). Since both types of bacteria are indicators of fecal contamination (MPCA, 2008a) from the same sources, the previous discussion about FC concentrations, including comparisons between the rivers, changes within their corridors, and the factors influencing these concentrations, also applies to *E. coli*.

The Minnesota water quality standard for *E. coli* is applicable during the April to October period. The standard states that *E. coli* concentrations should not exceed a monthly geometric mean of 126 organisms/100mL, and that no more than 10% of the monthly samples should exceed 1,260 organisms/100mL (Minn. Rules Chapter 7050). Since the *E. coli* concentrations shown in Figure 102 are 10-year median concentrations, no comparisons could be made to the water quality standard. Regardless, there are currently no *E. coli* impairments in the Mississippi, Minnesota, or St. Croix rivers within the metro area (MPCA, 2016a). However, as noted above, FC impairments exist in portions of the metro area Mississippi and Minnesota rivers, and TMDL implementation plans have been developed to improve water quality and the potential for recreational use.

Trends. MCES began monitoring *E. coli* in the rivers in 2005. Since QWTREND requires at least 15 years of data to evaluate long-term trends, it could not be used to analyze trends in *E. coli* concentrations.

Figure 102. Median *E. coli* Concentrations (#/100mL) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



Chloride (Cl)

Chloride exists naturally at low levels in the metro area's surface waters and plays a vital role in biological functions (MPCA, 2016d). However, high concentrations of Cl can be hazardous to aquatic life and can also affect drinking water sources, infrastructure, vehicles, plants, soil, pets, and wildlife (MPCA, 2016d). Cl is a permanent pollutant, meaning that once it enters a body of water, it is nearly impossible to remove efficiently (MPCA, 2016d). However, in rivers and streams, Cl is generally flushed out relatively quickly (days to weeks), compared to Cl in lakes and groundwater (Stefan et al., 2008). In highly developed areas, winter de-icing activity (that is, application of road salts) is typically the main source of Cl. In less developed areas with point source discharges, municipal WWTPs tend to be the primary Cl sources, typically due to water softening (MPCA, 2016d). Other sources of Cl include some fertilizers, biosolids, industrial wastewater, dust suppressants, and leachate from landfills and septic systems (MPCA, 2016d).

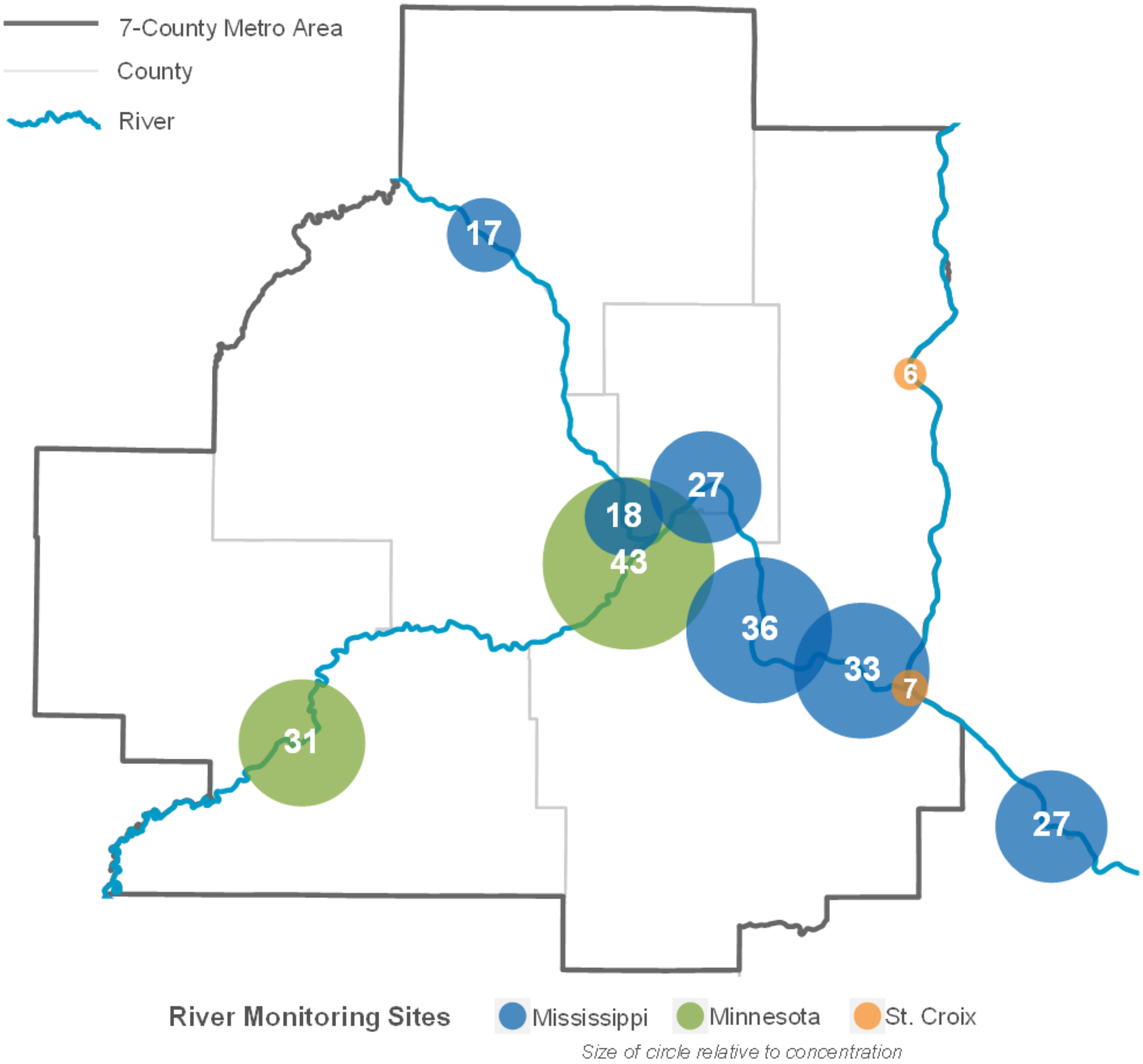
The main sources of Cl in metro area waters are winter road salts and water softeners (MPCA, 2016d). Approximately 349,000 tons of winter road salts are applied in the metro area each year, mainly from state, city, county, and commercial applicators (Sanders et al., 2007; Stefan et al., 2008). An estimated 70-78% of the Cl applied as road salt is retained in metro area soils, surface waters, and groundwater (MPCA 2016d; Novotny et al., 2009; Stefan et al., 2008). The remainder is exported out of the metro area via streams and rivers.

Salt used in water softeners can enter groundwater or surface water by passing through septic systems or through sewers to municipal WWTPs. The majority of Cl entering WWTPs in Minnesota originates from residential water softeners, contributing up to 90% in some municipalities (MPCA, 2016d). Unfortunately, most WWTPs are not equipped to remove Cl, and the current technology needed to do so is cost prohibitive (MPCA, 2016d; 2016e). As a result, Cl passes through most WWTPs and into surface waters. These point source discharges could have a proportionally greater impact on Cl concentrations in regional rivers during lower flow conditions.

Recent Conditions. Figure 103 displays the median Cl concentrations measured from 2006-2015 at each of the river monitoring sites in the metro area. As the three major rivers enter the metro area, the Minnesota River had the highest 10-year median Cl concentration (31 mg/L at Jordan), the St. Croix River had the lowest Cl concentration (6 mg/L at Stillwater), and the Mississippi River had an intermediate Cl concentration (17 mg/L at Anoka). Identifying the reason for the higher Cl concentration in the Minnesota River at Jordan is difficult, due to the current lack of quantitative information on salt usage in the contributing watersheds of these three rivers.

Some researchers have estimated the amount of salt applied within the metro area (Sanders et al., 2007), but there has not yet been an attempt to quantify the amount applied in upstream watersheds. Researchers at the University of Minnesota's Water Resources Center are currently investigating water softening salt usage across Minnesota. They have also mapped "hardness regions" of Minnesota using groundwater well data from the MPCA. The results show that the southwest regions of the state (within the Minnesota River watershed) generally have some of the hardest groundwater (Overbo 2017, personal communication). Assuming that more water softening salts are used to treat harder water, it then follows that more water softening salts are possibly being used in the Minnesota River watershed. Supporting this idea, the MPCA found that Cl in WWTP discharges appears to be a problem in about 100 communities across Minnesota, mostly in the southern and western regions of the state (MPCA, 2017d). As mentioned previously, a majority of Cl passing through WWTPs is generally associated with water softening (MPCA, 2016d).

Figure 103. Median Chloride Concentrations (mg/L) in the Mississippi, Minnesota, and St. Croix Rivers, 2006-2015



In the metro area of the Mississippi River, the 10-year median Cl concentrations are lowest in the upstream portion of the river, with little difference noted between Anoka and Lock and Dam 1. The higher Cl concentration in the Minnesota River (43 mg/L at Fort Snelling) contributes to a 50% increase in the Cl concentration in the Mississippi River between Lock and Dam 1 (18 mg/L) and Saint Paul (27 mg/L), although this increase at Saint Paul may also reflect the impacts of urban road salt usage.

The highest Cl medians on the Mississippi River occurred at Grey Cloud Island (36 mg/L) and Lock and Dam 2 (33 mg/L), likely reflecting contributions from the Metro WWTP and urban road salt usage. Since Cl was not monitored regularly at MCES WWTPs until 2015, a comparable 10-year median Cl concentration in the Metro WWTP discharge could not be calculated. However, as a general comparison, the median Cl concentration in the Metro WWTP discharge during the October 2015 to October 2017 period was 251 mg/L (MCES unpublished data accessed Dec. 2017). During the 2006-2015 period, the Metro WWTP contributed approximately 3% of the median Mississippi River flow.

Winter road salts use results in higher Cl concentrations during the winter months, as shown in the "Results" section. However, since road salts are only applied during part of the year, their influence is likely not as strongly reflected in the 10-year median Cl concentrations (Figure 103), compared to the effects of a year-round Cl source such as water softeners passing through WWTPs. The low Cl concentration in the St. Croix River (7 mg/L at Prescott) provides a dilution effect in the Mississippi River, causing Cl to decrease 18% between Lock and Dam 2 (33 mg/L) and Lock and Dam 3 (27 mg/L).

In the Minnesota River, the 10-year median Cl concentration increased 39% from Jordan (31 mg/L) to Fort Snelling (43 mg/L). This river reach transitions from rural/agricultural to urban (see "Study Area and Scope"), so the increased Cl concentration at Fort Snelling likely reflects road salt usage and the influence of the Blue Lake and Seneca WWTP discharges. As a comparison to Cl concentrations in the lower Minnesota River, median Cl concentrations in Blue Lake and Seneca WWTP discharges during the June 2015 to October 2017 period were 458 mg/L and 324 mg/L, respectively (MCES unpublished data accessed Dec. 2017). During the 2006-2015 period, both WWTPs combined to contribute approximately 2% of the median Minnesota River flow.

In the St. Croix River, Cl concentrations were very low compared to those in the Mississippi and Minnesota rivers. Of the three watersheds, the St. Croix watershed has the highest combined proportion of forests, grasses, and wetlands, and is the least developed (see "Study Area and Scope"). As a result, the impacts of Cl contributions from road salt usage and WWTPs are substantially reduced. Even in the metro reach of the St. Croix River, the Cl concentration only increased slightly, from 6 mg/L at Stillwater to 7 mg/L at Prescott.

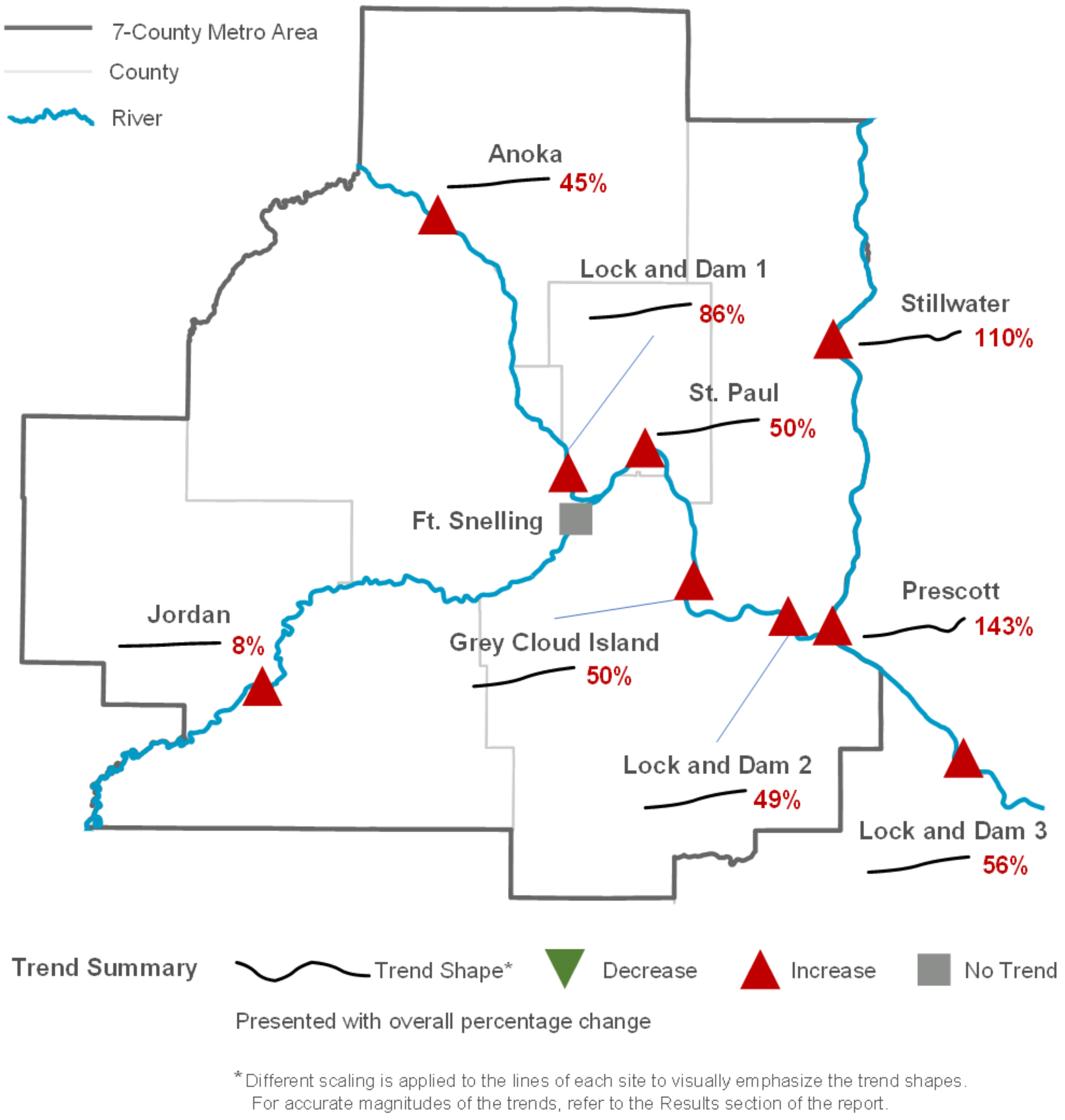
The Minnesota water quality standard for Cl, which is meant to protect aquatic life, limits the Cl concentration to an average of 230 mg/L over a 4-day period, to prevent chronic toxicity, and to 860 mg/L in a 24-hour period, to prevent acute toxicity (Minn. Rules Chapter 7050). There are currently no Cl impairments in the metro area Mississippi, Minnesota, and St. Croix rivers (MPCA, 2016a). However, 39 metro area waterbodies have Cl impairments, including 16 streams that eventually drain into the major rivers (MPCA, 2016e).

Since Cl does not degrade in the environment, it will likely continue to accumulate over time, especially in groundwater and lakes, unless significant mitigation actions are taken in the coming years (MPCA, 2016d; 2016e). To address the current Cl impairments in metro area waterbodies, the MPCA has completed a TMDL study (MPCA, 2016e) and developed a metro area chloride management plan (MPCA, 2016d).

31-Year Trends. Figure 104 displays overall trends in flow-adjusted Cl concentrations in the metro area Mississippi, Minnesota, and St. Croix rivers. Note that all Cl concentration trends were evaluated using data from the 1985-2015 period. Trend results show that, with the exception of the Minnesota River at Fort Snelling, Cl concentrations have significantly increased across all three rivers during the past 31 years. The smallest increase (8%) occurred in the Minnesota River at Jordan, the largest increases (110-143%) occurred in the St. Croix River, and intermediate increases (45-86%) occurred in the Mississippi River.

At river entry points to the metro area, the smallest increase in Cl concentration (8%) occurred at the Minnesota River entry point (Jordan), the largest increase (110%) occurred at the St. Croix River entry point (Stillwater), and an intermediate increase (45%) occurred at the Mississippi River entry point (Anoka). Although substantial increases in Cl concentrations were evident at Anoka and Stillwater, recent 10-year median Cl concentrations at these locations (Figure 103) were among the lowest in the three rivers.

Figure 104: Flow-Adjusted Chloride Concentration Trends in the Mississippi, Minnesota, and St. Croix Rivers, 1985-2015



Along the metro area Mississippi River, the greatest increase in Cl concentration (86%) occurred at Lock and Dam 1. Within the river reach from Anoka to Lock and Dam 1, numerous Mississippi River tributaries (Bass Creek, Bassett Creek, Elm Creek, Minnehaha Creek, Shingle Creek) have been listed by the MPCA (2016a) as impaired due to excessive Cl concentrations. High Cl concentrations in these streams and direct storm sewer discharges from Minneapolis and Saint Paul likely reflect salt usage for winter maintenance activities in largely urbanized watersheds. During the 2003-2012 period, median annual flow-weighted mean concentrations of Cl in Bassett and Minnehaha Creeks were 139 mg/L and 91 mg/L, respectively (MCES 2014). MPCA (2016d) notes that, when Cl concentrations in Bass, Elm, and Shingle creeks exceeded the chronic water quality criterion of 230 mg/L, average Cl concentrations were 1,600 mg/L, 1,105 mg/L, and 725 mg/L, respectively, during the 2003-2013 period.

In the Pool 2 reach of the metro Mississippi River, increases in Cl concentrations ranged from 49-50% at Saint Paul, Grey Cloud Island, and Lock and Dam 2. As at Lock and Dam 1, these increases likely reflect the impacts of urban salt usage via inputs from tributaries and storm sewer discharges in Saint Paul. Within the Ramsey-Washington Metro Watershed District, median annual flow-weighted mean concentrations of Cl in Battle and Fish Creeks were 134 mg/L and 111 mg/L, respectively, during the 2003-2012 period (MCES 2014).

Cl concentrations in these urbanized Mississippi River tributaries (Bassett, Minnehaha, Battle, and Fish Creeks) during the 2003-2012 period were much higher than concentrations in the Mississippi River at Anoka and Saint Paul. Cl inputs from the Metro WWTP may also have contributed to the increases in Cl concentrations downstream from Saint Paul. At Lock and Dam 3, the Cl concentration increased by 56%, very similar to the concentration increases observed in Pool 2 upstream. Weller and Russell (2016) noted that the average annual Cl concentration at Lock and Dam 2 increased by 81% during the 1985-2014 period.

In the Minnesota River, a slight increase in Cl concentration (8%) was apparent at Jordan, but no trend was detected at Fort Snelling. The Blue Lake and Seneca WWTP discharges and nine tributaries monitored by MCES flow into the Minnesota River between Jordan and Fort Snelling, each representing a Cl source. In general, watersheds of metro area Minnesota River tributaries are less urbanized than those of Mississippi River tributaries. Median annual flow-weighted mean concentrations of Cl ranged from 25-116 mg/L in the nine Minnesota River tributaries monitored by MCES during the 2003-2012 period (MCES 2014).

At the higher end, Cl concentrations in Nine Mile and Willow Creeks (Minnesota River tributaries with more urbanized watersheds), were 100 mg/L and 116 mg/L, respectively. Nine Mile and Sand creeks have been listed by MPCA as impaired for Cl (MPCA, 2016a). Stefan et al. (2008) studied the environmental impact of de-icing salt on metro area water quality and found that elevated Cl concentrations were related to increases in population and the amount of road salt usage per mile. Of the metro counties in his study, Scott and Carver counties, with tributaries draining to the Minnesota River, were the two counties that used the least amount of salt per lane mile per year. Although long-term Cl concentration trends in the Minnesota River have been minimal, the 2006-2015 median concentration at Fort Snelling (43 mg/L) is the highest metro area river concentration, which impacts the Cl concentration in the Mississippi River at Saint Paul (Figure 103).

In the St. Croix River, Cl concentrations at Stillwater and Prescott increased by 110% and 143%, respectively. These relatively high percentage increases are simply a reflection of small absolute increases in Cl concentrations that are the lowest of all metro area river concentrations (Figure 104). As noted above, the St. Croix watershed has the highest combined proportion of forests, grasses, and wetlands, and is the least developed (see “Study Area and Scope”). During the 2003-2012 period, median annual flow-weighted mean concentrations of Cl in four St. Croix River tributaries (Carnelian-Marine Outlet, Silver Creek, Browns Creek, and Valley Creek) ranged only from 10-20 mg/L (MCES, 2014). Furthermore, during the 2006-15 period, the St. Croix Valley WWTP contributed much less than 1% of the St. Croix River flow, making it a small source of Cl despite a median concentration of 215 mg/L from 2015-17 (MCES unpublished data accessed Dec. 2017).

Cl concentrations have been significantly increasing in Minnesota’s water bodies (MPCA, 2016d; 2016e). While monitoring has only been conducted on 10% of all metro area surface waters, 39 lakes and streams with excessive Cl concentrations have been listed by the MPCA (2016e) as impaired for aquatic life. Analysis of long-term trends in 14 of 22 lakes has also showed increasing Cl concentrations.

As indicated above, salt usage for winter de-icing activities in urban areas is a primary reason for increasing Cl concentrations trends in metro area rivers, especially the Mississippi River. Stefan et al. (2008) note that the use of salt for road de-icing has increased considerably since the 1940s, showing a long-term increasing trend in the metro area. Cl concentrations in metro area rivers exhibit a strong seasonal pattern (Figure 35, Figure 54, and Figure 73 in the “Results” section), with the highest concentrations evident during the winter months (December-March) when salt application is occurring.

MCES will continue to conduct monitoring of the three regional rivers, to further assess Cl sources and impacts, as well as long-term changes in Cl concentrations.

Summary

Recent Water Quality Conditions and Spatial Changes

A summary of recent 10-year median concentrations of all parameters at all monitoring sites is presented in Table 37. The parameters can generally be sorted into four groups, based on the patterns of their median concentrations across the metro area rivers:

1) Conductivity, BOD_5, TSS, TP, Chl-*a*, TN, and NO_3 – The median concentrations were highest in the Minnesota River, lowest in the St. Croix River, and intermediate in the Mississippi River.
2) NH_3, FC, and *E. coli* – The highest median concentrations occurred in the core of the metro area.
3) Temperature, pH, and, DO – The median concentrations were similar across the metro area.
4) Flow and Cl – The median concentrations had a unique pattern that did not fit in the other three groups.

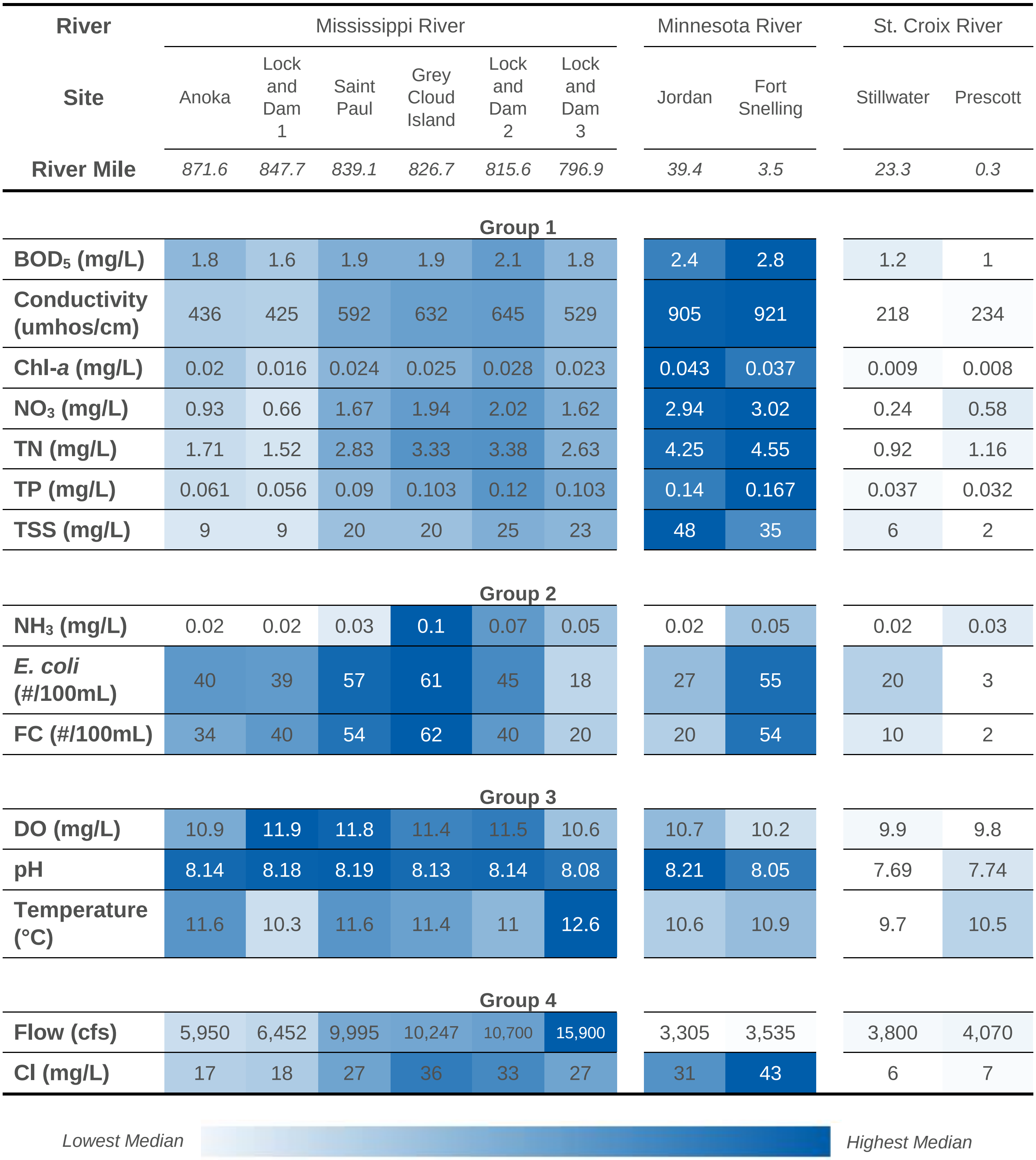
For the parameters in Group 1, stark water quality contrasts were apparent between the three rivers as they entered the metro area. The 10-year median concentrations of BOD_5, conductivity, TSS, TP, Chl-*a*, TN, and NO_3 were highest in the Minnesota River, intermediate in the Mississippi River, and lowest in the St. Croix River. This pattern was likely due to upstream differences between the three contributing watersheds. The Minnesota River watershed is primarily agricultural, the St. Croix River watershed has the highest percentage of forested land cover, and the Upper Mississippi River watershed is a more even mix of agriculture, forests, and wetlands. The major land cover types within each of the three watersheds are listed in Table 38 (refer to “Study Area and Scope” for more detail on land cover).

Additionally, the three watersheds span three different ecoregions. The Minnesota River watershed lies mostly within the Western Corn Belt Plains Ecoregion, whereas the Upper Mississippi River and St. Croix River watersheds are roughly split between Northern Lakes and Forests and North Central Hardwood Forests Ecoregions (USEPA, 2012a). These ecoregions have distinctive characteristics that can impact water quality in different ways. For example, the Minnesota River watershed lies in an ecoregion that has a younger geology and is more susceptible to erosion (MPCA, 2009a; 2009c).

For the parameters in Group 1, changes in concentrations occurred along all three metro area river reaches, but these changes were generally smaller than the differences between the rivers. Higher concentrations in the Minnesota River impacted the Mississippi River. The median concentrations in the Mississippi River increased between Lock and Dam 1 and Saint Paul due to the Minnesota River confluence, and concentrations generally remained elevated through the remainder of Pool 2. In contrast, lower concentrations in the St. Croix River caused concentrations in the Mississippi River to decrease between Lock and Dam 2 and Lock and Dam 3.

For the parameters in Group 2, the 10-year median concentrations of NH_3, FC, and *E. coli* were highest in the core of the metro area, specifically in the Mississippi River reach from Saint Paul to Grey Cloud Island, and in the Minnesota River at Fort Snelling. These parameters are typically associated with animal and human waste products, which tend to be more concentrated in populated regions due to WWTP and stormwater inputs.

Table 37. Patterns in Recent Water Quality Conditions in the Mississippi, Minnesota, and St. Croix Rivers (10-year median concentrations, 2006-2015)



River	Mississippi River						Minnesota River		St. Croix River	
Site	Anoka	Lock and Dam 1	Saint Paul	Grey Cloud Island	Lock and Dam 2	Lock and Dam 3	Jordan	Fort Snelling	Stillwater	Prescott
River Mile	*871.6*	*847.7*	*839.1*	*826.7*	*815.6*	*796.9*	*39.4*	*3.5*	*23.3*	*0.3*
					Group 1					
BOD_5 (mg/L)	1.8	1.6	1.9	1.9	2.1	1.8	2.4	2.8	1.2	1
Conductivity (umhos/cm)	436	425	592	632	645	529	905	921	218	234
Chl-*a* (mg/L)	0.02	0.016	0.024	0.025	0.028	0.023	0.043	0.037	0.009	0.008
NO_3 (mg/L)	0.93	0.66	1.67	1.94	2.02	1.62	2.94	3.02	0.24	0.58
TN (mg/L)	1.71	1.52	2.83	3.33	3.38	2.63	4.25	4.55	0.92	1.16
TP (mg/L)	0.061	0.056	0.09	0.103	0.12	0.103	0.14	0.167	0.037	0.032
TSS (mg/L)	9	9	20	20	25	23	48	35	6	2
					Group 2					
NH_3 (mg/L)	0.02	0.02	0.03	0.1	0.07	0.05	0.02	0.05	0.02	0.03
***E. coli* (#/100mL)**	40	39	57	61	45	18	27	55	20	3
FC (#/100mL)	34	40	54	62	40	20	20	54	10	2
					Group 3					
DO (mg/L)	10.9	11.9	11.8	11.4	11.5	10.6	10.7	10.2	9.9	9.8
pH	8.14	8.18	8.19	8.13	8.14	8.08	8.21	8.05	7.69	7.74
Temperature (°C)	11.6	10.3	11.6	11.4	11	12.6	10.6	10.9	9.7	10.5
					Group 4					
Flow (cfs)	5,950	6,452	9,995	10,247	10,700	15,900	3,305	3,535	3,800	4,070
Cl (mg/L)	17	18	27	36	33	27	31	43	6	7

Lowest Median *Highest Median*

Table 38. Top Three Land Cover Classifications within the Upper Mississippi, Minnesota, and St. Croix River Watersheds

Upper Mississippi River Watershed		**Minnesota River Watershed**		**St. Croix River Watershed**	
Land Cover	*% of watershed*	*Land Cover*	*% of watershed*	*Land Cover*	*% of watershed*
Forest	29	Agriculture	66	Forest	48
Agriculture	23	Grass	12	Agriculture	20
Wetland	20	Developed	7	Wetland	16

For the parameters in Group 3, the 10-year median temperatures, pH values, and DO concentrations did not vary across the metro area as much as the concentrations of other parameters. However, values for all Group 3 parameters were slightly lower in the St. Croix River.

In Group 4, the 10-year median flows and Cl concentrations showed more unique patterns. As expected, flows continuously increased as the rivers traveled downstream through the metro area. At river entry points, the Mississippi, Minnesota, and St. Croix rivers contributed 46%, 25%, and 29%, respectively, of the combined incoming river flow of 13,055 cfs. At Lock and Dam 3, where the Mississippi River exits the region, the median flow of 15,900 cfs represents a 22% increase due to metro area flow contributions, including tributaries, WWTPs, stormwater, and groundwater. Cl concentrations in regional rivers appear to be affected by both upstream watershed and metro area contributions, i.e. a mixture of Groups 1 and 2. Like Group 1, Cl concentrations were highest in the Minnesota River, intermediate in the Mississippi, and lowest in the St. Croix as the rivers entered the metro area, indicating differences caused by the upstream watersheds. Like Group 2, Cl concentrations increased notably near the core of the metro area, specifically in the Mississippi River reach from Saint Paul to Grey Cloud Island, and in the Minnesota River at Fort Snelling. Cl sources in the metro area include de-icers such as road salt and WWTP discharges, due primarily to salt usage in residential water softeners.

It is important to note that the discussion of median concentrations of the parameters evaluated in this report was based on observational results, meaning statistics were not used to test for significant differences in water quality between the sites, or to identify the factors responsible for any spatial differences. To do so would require a more in-depth and comprehensive analysis beyond this report.

Long-term Water Quality Trends

The statistical model QWTREND was used to evaluate long-term (1976-2015) flow-adjusted water quality trends in the metro area Mississippi, Minnesota, and St. Croix rivers. Table 39 summarizes the water quality trends for all parameters at all monitoring sites.

Table 39. Summary of Flow-Adjusted Water Quality Trends in the Metro Area Mississippi, Minnesota, and St. Croix Rivers, 1976-2015

River	Mississippi River						Minnesota River		St. Croix River	
Site	Anoka	Lock and Dam 1	Saint Paul	Grey Cloud Island[1]	Lock and Dam 2	Lock and Dam 3	Jordan	Fort Snelling	Stillwater	Prescott
River Mile	*871.6*	*847.7*	*839.1*	*826.7*	*815.6*	*796.9*	*39.4*	*3.5*	*23.3*	*0.3*
	Downward Trend									
BOD_5 (mg/L)	-34%	-44%	-48%	-57%	-62%	-63%	6%	-43%	BRL	BRL
TSS (mg/L)	-56%	-74%	-41%	-43%	-34%	-42%	-37%	-51%	-48%	-75%
TP (mg/L)	-44%	-43%	-46%	-59%	-36%	-37%	-44%[3]	-51%	-26%	-32%
NH_3 (mg/L)	BRL	BRL	BRL	-82%	BRL	BRL	BRL[3]	BRL	BRL	BRL
FC Bacteria (#/100mL)	-66%	PT	-96%	-98%	-67%	-77%	-88%	-61%	-59%	BRL
	Upward Trend									
TN (mg/L)	PT	PT	PT	PT	37%	PT	-29%[3]	51%	NT	31%
NO_3 (mg/L)	204%	187%	223%	302%	PT	181%	PT[3]	21%	24%	67%
Cl (mg/L)[2]	45%	86%	50%	50%	49%	56%	8%	NT	110%	143%
	Mixed Trend									
Chl-a (mg/L)	67%	-12%	34%	217%	PT	-47%	39%[3]	PT	72%	PT

NT: No Trend: A statistically significant trend model did not fit the data.

PT: Partial Trend: One of the sub-trends within the trend model was not statistically significant, so a representative overall percentage change could not be calculated.

BRL: Below Reporting Limit: More than 10% of the data were below than the lab's RL, so a representative overall percentage change could not be calculated.

(1) Period of record for Grey Cloud Island begins in 1978

(2) Period of record for Chloride begins in 1985

(3) Period of record begins in 1979

Decreasing Trend 🟩🟥 *Increasing Trend*

Trend analysis showed that regional river water quality has generally improved during the last four decades. Five of the nine parameters assessed (BOD_5, TSS, TP, NH_3, and FC) typically exhibited long-term decreasing trends in their flow-adjusted concentrations. Three parameters (TN, NO_3, and Cl) generally showed increasing trends, while one parameter (Chl-*a*) exhibited mixed trends during the assessment period.

Overall, the water quality trends observed in this report are similar to those observed by past studies of water quality trends in the metro area Mississippi, Minnesota, and St. Croix rivers. These studies have used MCES data from the same monitoring sites, although the statistical methods used for trend analysis and the periods of record differ.

For those parameters (BOD_5, TSS, TP, NH_3, and FC) that showed decreasing trends in this report (Table 39), studies by MCES (2004), Johnson (2009), and Lafrancois et al. (2013) also showed decreasing trends at Mississippi, Minnesota, and St. Croix River sites where study overlap occurred. Often, the magnitudes of these trends were very similar as well.

For those parameters (TN, NO_3, and Cl) that generally showed increasing trends in this report (Table 39), previous studies typically showed increasing trends at Mississippi, Minnesota, and St. Croix River sites where study overlap occurred. Lafrancois et al. (2013) found no trends for TN concentrations in the Mississippi River from Anoka to Lock and Dam 2 and in the Minnesota River at Fort Snelling, whereas this report found partially increasing trends for TN concentrations at the same sites, with the exception of 37% and 51% increases at Lock and Dam 2 and Fort Snelling, respectively. Studies by MCES (2004), Johnson (2009), Lafrancois (2013), and MPCA (2013) all agree that NO_3 concentrations are increasing in metro area rivers, although the magnitudes of these trends differ. Using the same statistical tool (QWTREND), MPCA (2013) found increasing NO_3 trend magnitudes that were comparable to those noted in this report. No previous studies have evaluated Cl trends in metro area rivers; however, Lafrancois et al. (2013) note that conductivity values increased significantly at metro area Mississippi River sites during the 1976-2005 period. Furthermore, studies by Stefan et al. (2008) and MPCA (2016) showed increasing trends for Cl concentrations in metro area lakes and elevated concentrations in some metro area streams. These studies help corroborate the increasing Cl concentration trends in metro area rivers, as noted in this report.

Although this report found mixed trends for Chl-*a* concentrations in metro area rivers, previous studies by MCES (2004) and Lafrancois et al. (2013) found either small increasing trends or no trends in Chl-*a* concentrations at metro area river sites where study overlap occurred.

When compared to previous studies, the trend magnitudes noted in this report are typically larger, because QWTREND identifies small and steep changes in concentrations, while non-parametric methods (such as the Seasonal Kendal Tau Test) show monotonic trends that are usually smoothed to reflect a general change over the entire assessment period. Therefore, discrepancies in trend magnitudes between this report and previous studies can be expected, as analysis periods and statistical methods are different.

Factors Contributing to Water Quality Changes

Water quality in the metro area Mississippi, Minnesota, and St. Croix rivers has changed dramatically during the last four decades. Although influenced to some extent by natural processes, these changes largely reflect human activities related to agriculture and urban development.

Decreasing trends in the flow-adjusted concentrations of BOD_5, TSS, TP, NH_3, FC indicate an improvement in water quality. Regulations on point source discharges and subsequent state-wide investments in wastewater treatment technology have greatly contributed to these decreasing trends. In the metro area, MCES investments in secondary treatment (post-1966) and advanced secondary treatment (post-1984) at seven WWTPs have substantially improved regional river water quality, especially in the Mississippi and Minnesota rivers, where the Metro, Blue Lake, and Seneca WWTPs are the largest point source contributors. Secondary treatment at MCES WWTPs has been especially effective at reducing BOD_5, TSS, and FC concentrations, while advanced secondary treatment has effectively reduced NH_3 and TP concentrations. Efforts to reduce combined sewer overflow (CSO) discharges to the metro Mississippi River have also yielded significant water quality benefits. Although more difficult to quantify, the collective actions taken to address urban and agricultural nonpoint sources of pollution during the past 40 years have undoubtedly contributed to improvements in regional water quality. Examples of these actions include MS4 permits and the application of BMPs to address urban stormwater runoff, implementation of TMDL plans to address water quality impairments, application of BMPs to address agricultural runoff, and legislation to limit the use of phosphorus in detergents and lawn fertilizers.

Conversely, increasing trends in the flow-adjusted concentrations of NO_3, TN and Cl indicate deteriorating water quality. Excessive nitrogen concentrations in surface waters are a major statewide concern. According to the MPCA's state-wide nitrogen study (MPCA, 2013), nitrogen sources contributing to Minnesota's waters include cropland tile drainage (37%), groundwater under cropland (30%), atmospheric deposition (9%), point sources (9%), forests (7%), agricultural runoff (5%), and septic systems (2%). Increasing NO_3 concentrations in regional rivers may be potentially linked to (1) changes in land management, agriculture practices, and climate; (2) increasing usage of fertilizers on agricultural croplands and urban lawns; (3) expansion of livestock and poultry production; and (4) increasing population. Although advanced secondary treatment at the MCES WWTPs has substantially reduced NH_3 concentrations, NO_3 concentrations have increased as a result. Increasing Cl concentrations at all metro area river monitoring sites (except Fort Snelling) reflects the increasing use of salt for winter de-icing activities and for water softening, primarily by residential households.

Current Water Quality Issues and Improvement Needs

Although concentrations of TSS, TP, and FC have significantly decreased in metro area rivers during the last four decades, water quality impairments currently exist in portions of the rivers, due to excess levels of these parameters. The metro Minnesota River is impaired due to excess levels of turbidity, nutrients, and FC bacteria. In the metro Mississippi River, the river reach downstream from the Minnesota River confluence through upper Lake Pepin is impaired due to excess levels of TSS, river reaches from Anoka to Lock and Dam 1 and from Saint Paul to Lock and Dam 2 are impaired due to excess levels of nutrients, and the river reach from Anoka to Saint Paul is impaired due to excess levels of FC bacteria. The metro St. Croix River (Lake St. Croix) is impaired due to excess levels of nutrients.

With nutrient impairments existing in all three rivers and nuisance algal blooms occurring, the lack of a clear response of Chl-*a* concentrations to decreasing trends in TP concentrations is concerning. As such, the river dynamics (flow, temperature, TSS and nutrient concentrations, and light availability) contributing to Chl-*a* concentrations need to be better understood to successfully implement management actions that restore water quality. Clearly, additional improvements are needed to meet water quality standards that protect aquatic life and benefit recreational use in regional rivers. To address current water quality impairments, MPCA and local partners are implementing TMDL plans that identify and reduce the sources of these pollutants. Continued monitoring will be key to determining whether management actions effectively address these current water quality impairments.

Increasing nitrogen (TN and NO_3) concentrations in metro area rivers are a significant regional and state-wide concern, as high nitrogen concentrations can impact drinking water sources, harm fish and aquatic life, and contribute to the oxygen-depleted dead zone in the Gulf of Mexico via the Mississippi River. Currently, no water quality impairments exist in regional rivers, based upon the drinking water standard for NO_3. However, future development of a NO_3 standard that protects aquatic life and/or the need to reduce NO_3 loads to the Gulf of Mexico will likely drive actions to reduce nitrogen concentrations in the state's surface waters, including metro area rivers.

Cl concentrations have significantly increased in metro area rivers during the last 31 years. As such, Cl is an emerging regional pollutant, largely due to the impacts of urbanization. Although there are currently no water quality impairments for Cl in metro area rivers, 39 metro area waterbodies have Cl impairments, including 16 streams that eventually drain into the major rivers (MPCA, 2016e). Since Cl does not degrade in the environment, it will likely continue to accumulate over time, especially in groundwater and lakes, unless mitigation actions are taken in the coming years (MPCA, 2016d; 2016e). To address the current Cl impairments in metro area waterbodies, the MPCA has completed a TMDL study (MPCA, 2016e) and developed a metro area chloride management plan (MPCA, 2016d).

RECOMMENDATIONS

Many partners are working to protect and restore Minnesota's water resources. Continued collective efforts will be needed to support state, regional, and local water resources management and pollution control programs. The following recommendations are provided in support of these efforts.

Water Quality Concerns and Recommendations for Action

- Unregulated nonpoint sources of pollution must be better managed to achieve water quality standards and goals that improve and protect the water quality of regional rivers. Passage of the Clean Water Act in 1972 resulted in: (1) major advances in wastewater treatment technology to address point sources of pollution via NPDES permits, and (2) the application of best management practices to address urban nonpoint sources of pollution through MS4 permits. These advances have resulted in marked improvements in regional river water quality. However, water quality impairments still exist for DO, TSS, nutrients (TP and Chl-*a*), and FC bacteria, and NO_3 and Cl are significant issues.

- The increasing trends in NO_3 concentrations across all three metro area rivers suggest that NO_3 management is a significant regional and state-wide issue. To help achieve reductions in the excessive nitrogen loads contributing to hypoxia in the Gulf of Mexico, Minnesota has established goals of a 20% reduction in nitrogen inputs to the Mississippi River by 2025 and a 45% reduction by 2040 (MPCA, 2014). Achieving these goals will require nitrogen reductions from cropland sources, point sources, and other nonpoint sources, which contribute 78%, 9%, and 13%, respectively, of the nitrogen load to the Mississippi River in Minnesota during an average precipitation year. Further, establishment of a state water quality standard for NO_3 is needed to protect aquatic life in Minnesota waters. Such a standard may also lead to implementation of measures that reduce NO_3 contributions from point and nonpoint sources.

- Although no Cl-related water quality impairments currently exist in metro area rivers, the increasing trends in Cl concentrations across all three rivers suggest that Cl management is a significant regional issue. Increasing Cl concentrations in the three rivers reflect increasing concentrations in contributing tributaries and stormwater discharges, with 16 tributaries exhibiting Cl impairments. The MPCA's chloride management plan (MPCA, 2016d) identifies methods for reducing chloride use in the metro area without impacting public safety. However, more education and outreach are needed, as citizens and municipalities can take actionable steps to help address this issue.

- Although conventional water quality pollutants are evaluated in this report, emerging contaminants associated with wastewater treatment are not. Examples of these contaminants include pharmaceutical products, personal care products, and microplastics. Additional funding for research and river monitoring of emerging contaminants are needed to better evaluate this issue.

Monitoring Recommendations

- Continue long-term monitoring of metro area rivers, to evaluate ongoing changes and improvements in water quality.

- Continue long-term monitoring of metro area streams, to determine the impacts they are having on regional river water quality, as well as to assess if tributary watershed improvements are improving the quality of downstream resources.

- Explore where the installation and use of continuous monitoring equipment at regional river monitoring sites could be expanded to better understand patterns and trends for parameters such as DO, temperature, turbidity/TSS, NO_3, Chl-*a*, and Cl, as a supplement to routine chemistry analysis.

- Invest further in strong working relationships with local, state, and federal agencies conducting water monitoring in Minnesota. Capitalize on the unique expertise of each of these agencies to create a comprehensive picture of river water quality.
- Continue to align monitoring, laboratory, and data analysis approaches, methods, and tools.

Assessment Recommendations

- Assess the pollutant load dataset (1976-present) for regional rivers, to evaluate comparative load contributions and long-term trends. Information on pollutant loads will complement the results presented here on recent and long-term concentrations of water quality parameters, providing a more complete picture of regional river conditions.
- Assess the biological monitoring data (macroinvertebrates, zooplankton, periphyton, and phytoplankton) for regional rivers, using available indices and indicators to incorporate the broader concept of water resource integrity. Collection of biological information is necessary to supplement chemical information collected, thereby providing a better understanding of the health of aquatic life.
- Conduct mechanistic studies and/or modeling, so that the interrelationships between flow, temperature, nutrients, TSS, light, and Chl-*a* in regional rivers can be better understood. This is crucial in understanding which factor(s) is contributing most to eutrophication issues and which should be targeted to manage the existing nutrient impairments along all three rivers
- Assess the continuous monitoring information collected at several regional river monitoring sites, to better understand patterns and trends for parameters such as DO, temperature, pH, conductivity, and NO_3.
- Examine long-term changes in river flows and their associated impacts on water quality.
- Continue to evaluate river water quality trends, to determine if observed water quality improvements for BOD_5, TSS, TP, NH_3, FC can be continued or at least maintained, and if water quality improvements can be achieved for Chl-*a*, TN, NO_3, and Cl.
- Update stream water quality trends, to determine if tributary watershed improvements and best practices, land use changes, implementation of regional and local policy and other factors are improving the quality of metro area streams and the receiving waters to which they discharge.
- Determine whether the MCES river and stream monitoring and assessment programs are positioned to evaluate the long-term impacts of climate change on regional water resources.

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GLOSSARY

Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
ATP	Alternative Test Procedure
Bio-P	Biological Phosphorus (Removal Technology)
BMP	Best Management Practice
BOD	Biochemical Oxygen Demand
BOD_5	5-day Biochemical Oxygen Demand
BRL	Below Reporting Limit
cfs	Cubic Feet per Second
Chl-*a*	Corrected Chlorophyll-*a*
Cl	Chloride
CSO	Combined Sewer Overflow
DO	Dissolved Oxygen
E. coli	*Escherichia coli* bacteria
EOR	Emmons & Olivier Resources, Inc.
EPA	(United States) Environmental Protection Agency
FC	Fecal Coliform bacteria
lb/gal	Pound per Gallon
MCES	Metropolitan Council Environmental Services
Metro area	Twin Cities Metropolitan Area
MGD	Million Gallons per Day
mg/L	Milligrams per Liter
MN	Minnesota
MnDNR	Minnesota Department of Natural Resources
MPCA	Minnesota Pollution Control Agency
MS4	Municipal Separate Storm Sewer System
MWCC	Metropolitan Waste Control Commission
NH_3	Ammonia-Nitrogen
NO_2	Nitrite-Nitrogen
NO_3	Nitrate-Nitrogen

NO_3-NO_2	Sum of Nitrate- and Nitrite-Nitrogen
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NPS	National Park Service
NT	No Trend
P	Phosphorus
PCB	Polychlorinated biphenyl
PFOS	Perfluorooctanesulfonic acid
PT	Partial Trend
QWTREND	Quality of Water Trend
RL	Reporting Limit
SCWD	Scott County Watershed District
SM	Standard Methods for the Examinations of Water and Wastewater
SWCD	Soil and Water Conservation District
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UMN	University of Minnesota
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
USU	Utah State University
WD	Watershed District
WHO	World Health Organization
WMO	Watershed Management Organization
WWTP	Wastewater Treatment Plant

Definitions

Akaike Information Criteria (AIC)

Model selection criteria based on in-sample fit to estimate the likelihood of a model to predict/estimate the future values. The criteria provides a relative measure of goodness-of-fit of the statistical trend model to measured concentrations.

Ammonia

The form of nitrogen produced when bacteria and fungi break down organic matter. It is generally only elevated near sources of animal or human waste. High ammonia is toxic to aquatic life. In this report, ammonia-nitrogen (NH_3) refers to the sum of nitrogen in un-ionized ammonia and ammonium.

Below Reporting Limit (BRL)

A term unique to this report used to indicate trend results where more than 10% of the data were at or below the analytical reporting limit. In this case, a percent change was not calculated for the overall assessment period, but the trend shape and direction were able to be used as exploratory results.

Best Management Practices (BMP)

The US Environmental Protection Agency uses the term BMP to describe a type of water pollution control. BMPs can be structures, like rain gardens, ponds, swales, and stabilized stream banks. BMPs can also be non-structural, for example cleaning up pet waste or ordinances banning application of phosphorus-based fertilizers. See the Minnesota State Stormwater Manual (posted on the Minnesota Pollution Control Agency's website, for additional examples of BMPs.

Biological Oxygen Demand (BOD)

Measure of the amount of oxygen required by bacteria to consume organic matter in water. Measured over a period of time, typically 5 days at 20°C (BOD_5). it is widely used as an indication of the organic quality of water and is often used as a robust surrogate of the degree of organic pollution of water.

Chloride (Cl)

A chemical commonly used in winter ice removal salts and home water softening products. When the snow and ice melt off the roads, parking lots, and sidewalks, Cl is carried into our streams. High concentrations of Cl can be harmful to aquatic life.

Chlorophyll

A green pigment found in plants which is necessary for photosynthesis. Chlorophyll-*a* is a specific form of chlorophyll. Analysis of chlorophyll-*a* can be corrected or uncorrected for pheophytin, which is a natural by-product of chlorophyll degradation (i.e. dead plant cells). As such, corrected chlorophyll-*a* measures the amount of chlorophyll-*a* in living plant cells and can be used to represent the amount of algae growing in the water column. Excess growth of algae depletes the water system of oxygen as the algae die off, choking out the aquatic life which is dependent on oxygen for survival. Algae growth is dependent on photosynthesis, so chlorophyll tends to rise and fall with the seasons as temperatures and sunlight hours shift when the excessive nutrients (mostly nitrogen and phosphorus) exist.

Chlorophyll-*a*

A specific form of chlorophyll. See "Chlorophyll"

Climate Normal

The 30-year average of a climate variable such as temperature or precipitation. Climate normal is generally updated every decade.

Concentration

The amount of a substance or pollutant per volume of water. MCES typically uses mass per unit volume of water, in units of milligram per liter (mg/L). Alternatively, concentration could be expressed in other units, such as pounds per gallon (lb/gal) or micrograms per liter (µg/L). Concentration can also be expressed as count per unit volume of water, such as organism count per 100 milliliters of water (#/100mL), a common measurement for bacteria.

Conductivity

A measure of the conduction of electricity through water; can be used to determine the total dissolved salts content.

Contaminant

Any chemical, microbe, or other material that is not found in pure water and that can make water unsuitable for its intended use. Some contaminants only affect aesthetic qualities such as appearance, taste, or odor of the water, while others can produce adverse health effects.

Corrected Chlorophyll-*a* (Chl-*a*)

Pheophytin corrected chlorophyll-*a*; the form of chlorophyll commonly used by water quality professionals to evaluate the condition of a site because it represents the amount of living algal biomass in the water. See “Chlorophyll”.

De-Icier

A substance, often containing chloride, which is used to remove or prevent the formation of ice.

Diel

Having a 24-hour cycle or pattern.

Discharge

Wastewater, treated or untreated, that flows out of a wastewater treatment plant, or industrial outfall. Also frequently called effluent.

Dissolved Oxygen (DO)

The amount of oxygen gas dissolved in water, which can come from the atmosphere and photosynthesis. Sufficient oxygen levels are necessary for the survival of most aquatic life and the health of the river ecosystem.

Ecoregion

Land areas that have similar ecosystems, specifically sharing characteristics such as geology, landforms, soil type, vegetation, land use, wildlife, and hydrology.

Escherichia coli (*E. coli*)

Bacterium found in the intestinal tracts of warm blooded animals, including humans. Used as an indicator of the presence of pathogenic organisms.

Eutrophication

The process by which a body of water becomes enriched in nutrients that stimulate the growth of aquatic plant life, especially algae.

Extirpation

The extinction of a species from a defined geographic area. Sometimes also referred to as Local Extinction.

Fecal Coliform

Bacterium present in the intestinal tracts and feces of humans and other warm-blooded animals. Drinking water with fecal coliform can cause diarrhea and other gastrointestinal illnesses. Often reported as organisms (or colony forming units, CFU) per 100 mL of water (#/100mL).

Flow

Flow can refer to both the rate of water flowing in a river at any particular time (cubic feet per second, or gallons per second) or the total amount of water delivered by the river into a larger body of water (gallons per year).

Flow-Adjusted Trends

Water quality trends with the removed effects of flow and water volume on concentrations. Flow-adjusted trends can be used to better understand how non-flow related factors such as pollution reduction efforts and investments contribute to improvements in river water quality.

Grab Sample

A water sample collected at a single point in time.

Impaired

A status given to a body of water when its water quality does not meet one or more water quality standards.

Kendall Tau Test

A rank-based statistical test to measure the relationship between two variables.

Load

The mass (as expressed in pounds or kilograms) of constituent or pollutant transported by a river or stream during a specified time period (for example, pounds-per-year). MCES typically uses the computer tool Flux32 to estimate stream and river loads using sample concentrations and daily average flow values.

Lower Mississippi River

Within Minnesota and throughout this report, the Lower Mississippi River is defined as the part of the Mississippi River downstream from the St. Croix River confluence at river mile 811

Mean

A central tendency statistic used to measure the average value in a dataset, often simply called the average. The mean is the sum of all numbers in a dataset divided by how many numbers there are.

Median

A central tendency statistic used to measure the most “typical” value in a dataset. The median is the value which lies in the middle of a dataset ordered numerically, meaning half the numbers in the dataset are below the median and half are above.

Monotonic Trend

A trend that only moves in one direction, either consistently increasing or decreasing over time

Nitrate

A nutrient necessary for aquatic growth, but excessive amounts can lead to problems like algae blooms, decreased oxygen levels, and fish kills. In addition, high nitrate levels in drinking water can lead to methemoglobinemia, a blood condition usually affecting infants that is caused by nitrate molecules interfering with the ability of red blood cells to transport oxygen efficiently. Common sources of nitrate include fertilizers, plant debris, and septic and municipal wastewater treatment systems. In this report, nitrate-nitrogen (NO_3) refers to the amount of nitrogen in nitrate.

Non-Monotonic Trend

A trend that changes direction, alternating between increasing and decreasing over time

Nonpoint Source

A source of pollution that does not have a clear and identifiable location; the source is diffuse and comes from a wide area. Main nonpoint sources include tributaries, direct runoff into rivers from adjacent land, and atmospheric deposition.

Nutrient

The most common nutrients of concern in stream water quality are nitrogen (often measured as nitrate) and phosphorus. Low levels of nutrients do occur naturally and are important for stream health. However, too many nutrients (from lawn or agricultural fertilizers, malfunctioning septic systems, grass clippings, and manure and pet wastes) can be harmful to stream health. See “Eutrophication”.

p-value

Calculated probability used in hypothesis testing to help users support or reject the null hypothesis for a given statistical model. In this study, the *p*-value was used to test statistical significance of a trend model or trend.

Parameter

Used in this report to refer to a measurable factor of water quality (flow, temperature, chloride concentration, etc.).

Partial Trend (PT)

A term unique to this report used to indicate trend results where one or more sub-trends in the trend model were not significant. In this case, a percent change was not calculated for the overall assessment period, but the trend shape and direction were able to be used as exploratory results.

Pattern

A general term referring to a form or shape in data

pH

A measurement of acidity. pH values range from 0 (the most acidic) to 14 (the least acidic). A value of 7 is neutral.

Phosphorus

A nutrient that can contribute to water quality issues in lakes and streams. Low levels of phosphorus do occur naturally and are important for stream health. However, too much phosphorus (from lawn or agricultural fertilizers, malfunctioning septic systems, grass clippings, and manure and pet wastes) can be harmful to stream health. See “Total Phosphorus” and “Eutrophication”.

Point source

A source of pollution that has a clear and identifiable location such as a pipe. Most of the point source discharges are from wastewater treatment plants and industrial facilities.

QWTREND

Quality of Water Trend, which is a statistical program developed by the USGS to analyze long-term flow-adjusted water quality trends. The program is a statistical parametric time series model that accounts for seasonality, complex flow-related variability, and complex serial correlation structure to detect trends in flow-adjusted concentrations.

Rain Garden

A best management practice used for treating runoff from impervious urban areas such as roofs, driveways, sidewalks, parking lots, and compacted lawns. A rain garden is a depressional area with plants where rainwater runoff from the impervious surfaces is directed to allow the runoff to soak into the ground, reducing the runoff and absorbing pollutants.

Reporting Limit (RL)

The lowest concentration that is reported by a laboratory for a specific analytical method.

Runoff

The flow of water over Earth’s surface, from rainfall, melting snow and ice, or other flow sources.

Sediment

Sediment is made up of sand, silt, or clay particles. Sediment is naturally present in all streams, but excessive sediment can enter the stream from construction sites or eroded stream banks and gullies. Excess sediment in waterbodies decreases the light available for plant growth, increases water temperature, clogs gills of fish, and smothers the habitat of valuable aquatic insects. In this report, “Total Suspended Solids” is often used to refer to the amount of sediment in water.

Standard

Water quality standard; Specific numeric or narrative limits set for certain water quality parameters in a waterbody. Standards are developed to protect and maintain the intended use of a waterbody, such as recreation, drinking water supply, and/or protecting aquatic life. If a standard is exceeded, the MPCA can designate the waterbody as “Impaired” and require the creation of a Total Maximum Daily Load plan.

Stormwater

Water from rainfalls and melting snow and ice.

Sub-trend

A trend period which exists within a non-monotonic trend model identified using QWTREND. A sub-trend can be either significant or non-significant within a trend model. See “QWTREND”.

Surface Water

Water that remains on the earth’s surface, in oceans, rivers, streams, lakes, wetlands, or reservoirs.

Trend

A statistically determined direction of data over time

Trend Model

The combined trend that could include either one or multiple sub-trends identified by QWTREND, which spans the entire assessment period. See “QWTREND”.

Total Maximum Daily Load (TDML)

A calculation of the maximum amount of a pollutant that a water body can receive and still meet water quality standards established by the Minnesota Pollution Control Agency.

Total Phosphorus (TP)

A nutrient that is necessary for the growth of aquatic organisms, excessive amounts can lead to algae blooms, decreased oxygen levels, and fish kills. Erosion of fertilized soils is a primary source of phosphorus to streams or rivers. Total Phosphorus (TP) is the total mass of soluble and particulate phosphorus in a volume of water. See “Phosphorus”.

Total Suspended Solids (TSS)

Solid material, organic and inorganic, that is suspended in the water, including silt, sand, soil, and algae. TSS in a stream can be expressed as a concentration (in units like milligrams per liter) or a mass load (in units like pounds per year). See “Sediment”.

Turbidity

The amount of small particles of solid matter suspended in water as measured by the amount of scattering and absorption of light rays caused by the particles.

Twin Cities Metropolitan Area

The seven-county region surrounding Minneapolis and Saint Paul, consisting of Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington counties.

Upper Mississippi River

Defined in the report as the part of the Mississippi River upstream from the St. Croix River confluence at river mile 811.

Watershed

A land area defined by topography, soil and drainage characteristics that collects water that flows to a common point. The watershed of a river is all land area that drains to the river along its entire length.

z-score

Measure of standard deviation from the mean a data point is. In this study, it was used to estimate the approximate p value of individual trends.

APPENDIX: STATISTICAL ANALYSIS OF LONG-TERM WATER QUALITY TRENDS USING QWTREND

To understand how regional river water quality has changed during the last several decades, the USGS statistical model QWTREND was used to quantify long-term water quality trends of three major rivers in the metro area. The analysis was performed for selected water quality parameters at six sites on the Mississippi River, two on the Minnesota River and two on the St. Croix River. The selected parameters included BOD_5, TSS, TP, Chl-*a*, TN, NO_3, NH_3, FC and Cl. Due to availability of measurements, the trend assessment periods may vary by parameter and site by site.

In the trend results that follow, unless otherwise indicated, all trends use flow-adjusted concentration and statistically significant at 95% confidence level ($p < 0.05$). No trend was reported if combined trend models or sub-trends were not statistically significant. In addition, numerical trend results were not reported for NH_3 (except for the Mississippi River at Grey Cloud Island) because more than 10% of measured NH_3 concentrations were below the analytical report limits. This also applied to BOD_5 in the St. Croix River at Stillwater and Prescott and to FC in the St. Croix River at Prescott. However, in each of these cases, the shape and direction of the trend was still reported as an exploratory result to determine if an overall increasing or decreasing trend was apparent (Vecchia, 2017 personal communication)

Mississippi River

Anoka (UM 871.6)

Measurements of the select water quality parameters at Anoka (river mile 871.6) were available from 1976 to 2015, except Cl, which was available from 1985 to 2015. The daily flow was estimated for analysis using USGS records measured at the Mississippi River Anoka station (USGS 05288500), Elm Creek station (USGS 05287890), and MCES record at Rum River station. Because QWTREND requires a complete daily flow record for the measurement periods of water quality plus the precedent five years, estimated daily flow from 1971 were used for analysis. The statistical trend results using QWTREND are presented in Table 40 and Figure 105.

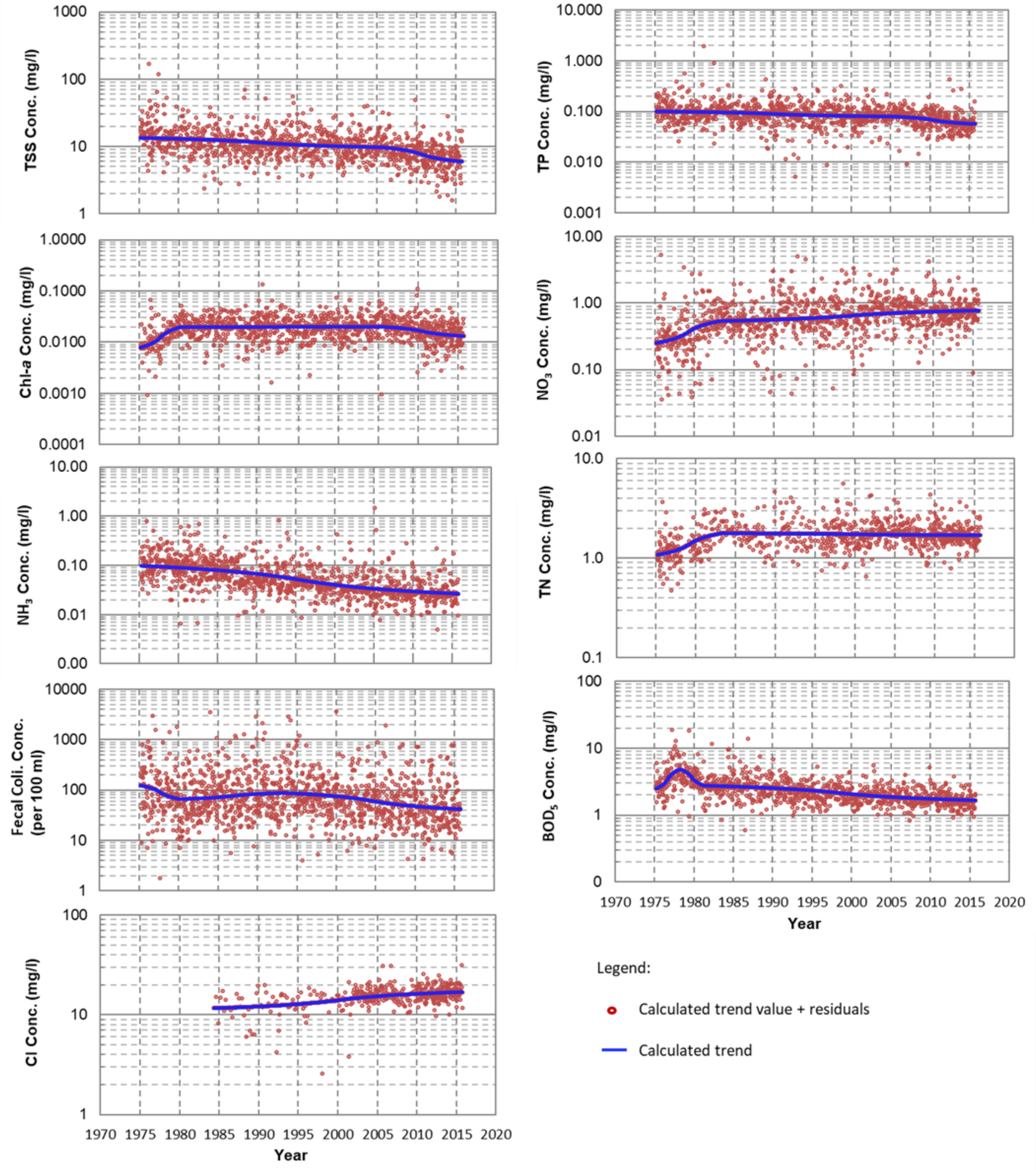
Table 40: QWTREND Results for the Mississippi River at Anoka

Parameter	Trend Period	Flow-Adjusted Concentration (mg/L)	Change (%)	Change Rate (mg/L/yr)	*p*-value	Trend
TSS	1976 – 2005	13.4 – 9.8	-27	-0.12	< 0.0001	⬇
	2006 – 2015	9.8 – 6.0	-39	-0.38	< 0.0001	⬇
TP	1976 – 2005	0.100 – 0.079	-21	-0.00071	0.0002	⬇
	2006 – 2015	0.079 – 0.057	-29	-0.0023	< 0.0001	⬇
Chl-*a*	1976 – 1980	0.008 – 0.019	149	0.0024	< 0.0001	⬆
	1981 – 2005	–	–	–	0.85	No trend
	2006 – 2015	0.020 – 0.013	-34	-0.00069	< 0.0001	⬇
NO_3	1976 – 1983	0.25 – 0.54	112	0.035	< 0.0001	⬆
	1984 – 2015	0.54 – 0.77	44	0.0073	< 0.0073	⬆
NH_3	1976 – 2015	–	–	–	BRL	⬇
TN	1976 – 1983	1.09 – 1.79	64	0.088	< 0.0001	⬆
	1984 – 2015	–	–	–	0.44	No trend
FC*	1976 – 1980	124 – 66	-46	-11.5	0.008	⬇
	1981 – 1993	66 – 88	33	1.7	0.030	⬆
	1994 – 2015	88 – 42	-52	-2.1	< 0.0001	⬇
BOD_5	1976 – 1978	2.5 – 4.8	93	0.77	< 0.0001	⬆
	1979 – 1981	4.8 – 2.9	-40	-0.64	< 0.0001	⬇
	1982 – 2002	2.9 – 1.9	-32	-0.044	< 0.0001	⬇
	2003 – 2015	1.9 – 1.6	-15	-0.022	< 0.0001	⬇
Cl	1985 – 2015	11.6 – 16.9	45	0.17	< 0.0001	⬆

BRL: Below Reporting Limit - More than 10% of measured concentrations were below the analytical report limits. QWTREND was only used for exploratory analysis to understand trend shape and direction.

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 105: Water Quality Trends for the Mississippi River at Anoka



Lock and Dam No. 1 (UM 847.7)

Measurements of the select water quality parameters at Lock and Dam 1 (river mile 847.7) were available from 1976 to 2015, except Cl, which was available from 1985 to 2015. The daily flows from 1971 to 2015 measured by USACE at the same location were used for analysis. The statistical trend results using QWTREND are presented in Table 41 and Figure 106.

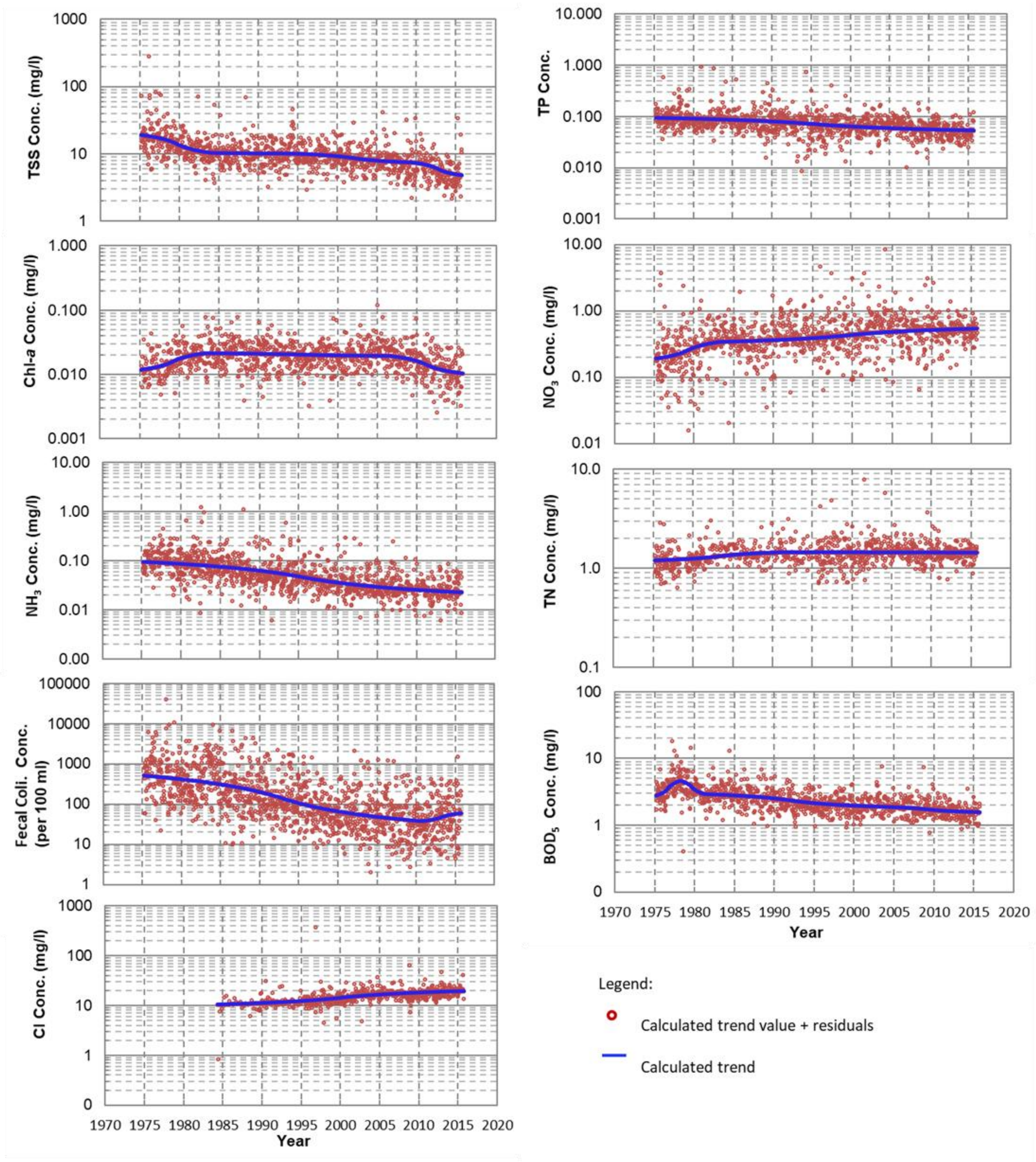
Table 41: QWTREND Results for the Mississippi River at Lock and Dam 1

Parameter	Trend Period	Flow-Adjusted Concentration (mg/L)	Change (%)	Change Rate (mg/L/yr)	*p*-value	Trend
TSS	1976 – 1984	18.9 – 10.1	-46	-0.97	< 0.0001	⬇
	1985 – 1994	–	–	–	0.76	No trend
	1995 – 2009	10.0 – 7.4	-26	-0.18	< 0.0001	⬇
	2010 – 2015	7.4 – 4.8	-35	-0.42	< 0.0001	⬇
TP	1976 – 2015	0.093 – 0.053	-43	-0.0010	< 0.0001	⬇
Chl-*a*	1976 – 1983	0.012 – 0.021	81	0.0012	< 0.0001	⬆
	1987 – 2006	–	–	–	0.21	No trend
	2007 – 2015	0.019 – 0.010	-46	-0.0010	< 0.0001	⬇
NO_3	1976 – 1983	0.19 – 0.34	80	0.019	0.0004	⬆
	1984 – 2015	0.34 – 0.54	60	0.0064	< 0.0001	⬆
NH_3	1976 – 2015	–	–	–	BRL	⬇
TN	1976 – 1991	1.20 – 1.45	20	0.015	0.0054	⬆
	1992 – 2015	–	–	–	0.88	No trend
FC*	1976 – 2010	510 – 37	-93	-13.5	< 0.0001	⬇
	2011 – 2015	–	–	–	0.10	No trend
BOD_5	1976 – 1978	2.8 – 4.6	67	0.62	< 0.0001	⬆
	1979 – 1981	4.6 – 2.9	-37	-0.56	< 0.0001	⬇
	1982 – 2002	2.9 – 1.9	-35	-0.049	< 0.0001	⬇
	2003 – 2015	1.9 – 1.6	-18	-0.026	< 0.0001	⬇
Cl	1985 – 2015	10.4 – 19.3	86	0.29	< 0.0001	⬆

BRL: Below Reporting Limit - More than 10% of measured concentrations were below the analytical report limits. QWTREND was only used for exploratory analysis to understand trend shape and direction.

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 106: Water Quality Trends for the Mississippi River at Lock and Dam 1



Saint Paul (UM 839.1)

Measurements of the select water quality parameters at Saint Paul (river mile 839.1) were available from 1976 to 2015, except Cl, which was available from 1985. The daily flow from 1971 to 2015 measured by USGS at its Saint Paul station (USGS 05288500) was used for analysis. The statistical trend results using QWTREND are presented in Table 42 and Figure 107.

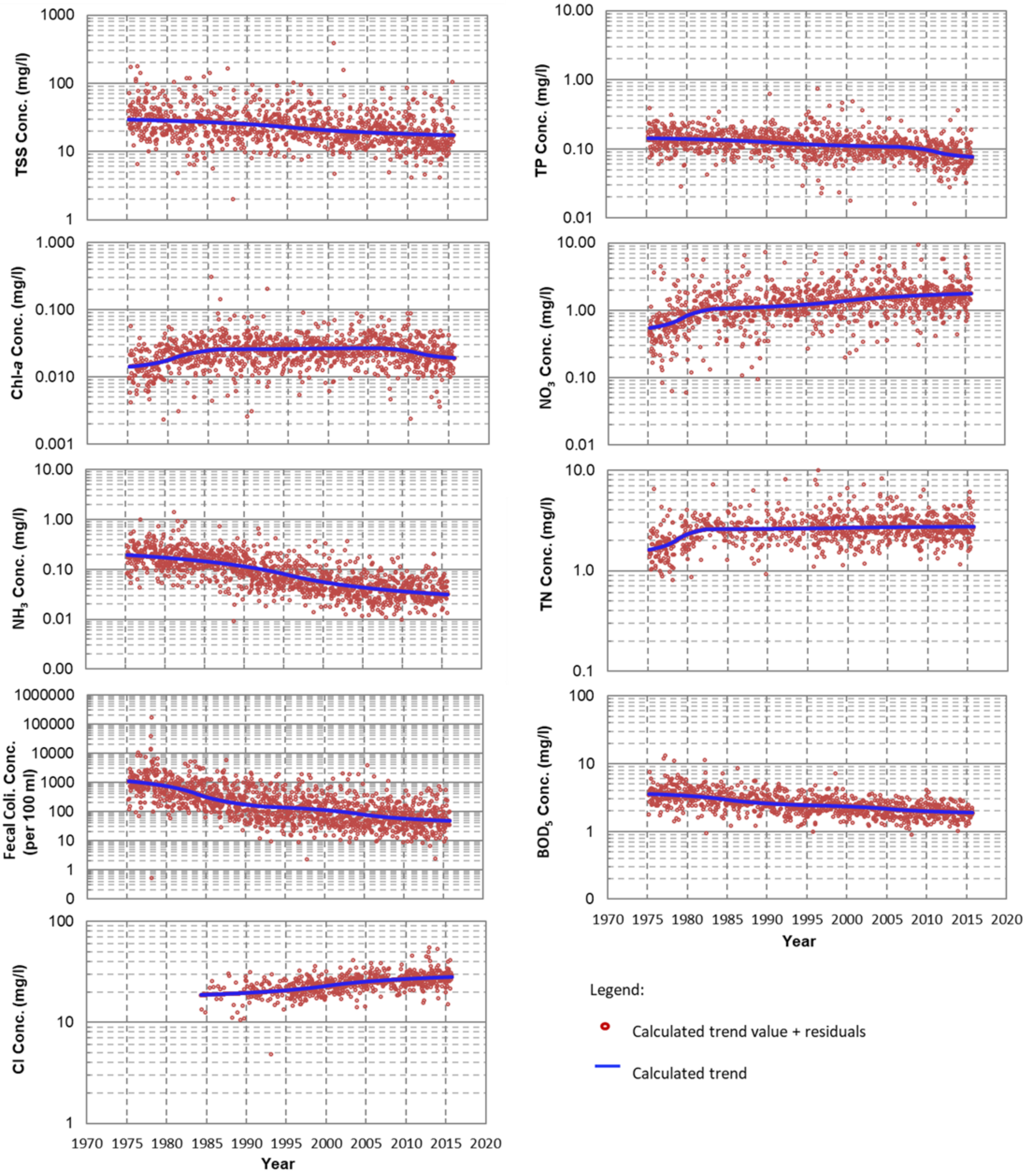
Table 42: QWTREND Results for the Mississippi River at Saint Paul

Parameter	Trend Period	Flow-Adjusted Concentration (mg/L)	Change (%)	Change Rate (mg/L/yr)	*p*-value	Trend
TSS	1976 – 2015	29.4 – 17.3	-41	-0.30	< 0.0001	⬇
TP	1976 – 2006	0.142 – 0.107	-24	-0.0011	< 0.0001	⬇
	2007 – 2015	0.108 – 0.077	-28	-0.0033	< 0.0001	⬇
Chl-*a*	1976 – 1986	0.014 – 0.026	79	0.0010	< 0.0001	⬆
	1987 – 2006	–	–	–	0.60	No trend
	2007 – 2015	0.027 – 0.019	-28	-0.00083	0.0013	⬇
NO_3	1976 – 1983	0.54 – 1.04	93	0.063	0.00013	⬆
	1984 – 2015	1.04 – 1.78	71	0.023	< 0.0001	⬆
NH_3	1976 – 2015	–	–	–	BRL	⬇
TN	1976 – 1982	1.60 – 2.58	61	0.14	< 0.0003	⬆
	1983 – 2015	–	–	–	0.45	No trend
FC*	1976 – 1992	1083 – 146	-86	-55.1	< 0.0001	⬇
	1993 – 2015	146 – 48	-67	-4.3	< 0.0001	⬇
BOD_5	1976 – 1994	3.6 – 2.4	-32	-0.061	< 0.0001	⬇
	1995 – 2015	2.4 – 1.9	-23	-0.027	< 0.0001	⬇
Cl	1985 – 2015	18.7 – 28.0	50	0.30	< 0.0001	⬆

BRL: Below Reporting Limit - More than 10% of measured concentrations were below the analytical report limits. QWTREND was only used for exploratory analysis to understand trend shape and direction.

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 107: Water Quality Trends for the Mississippi River at Saint Paul



Grey Cloud Island (UM 826.7)

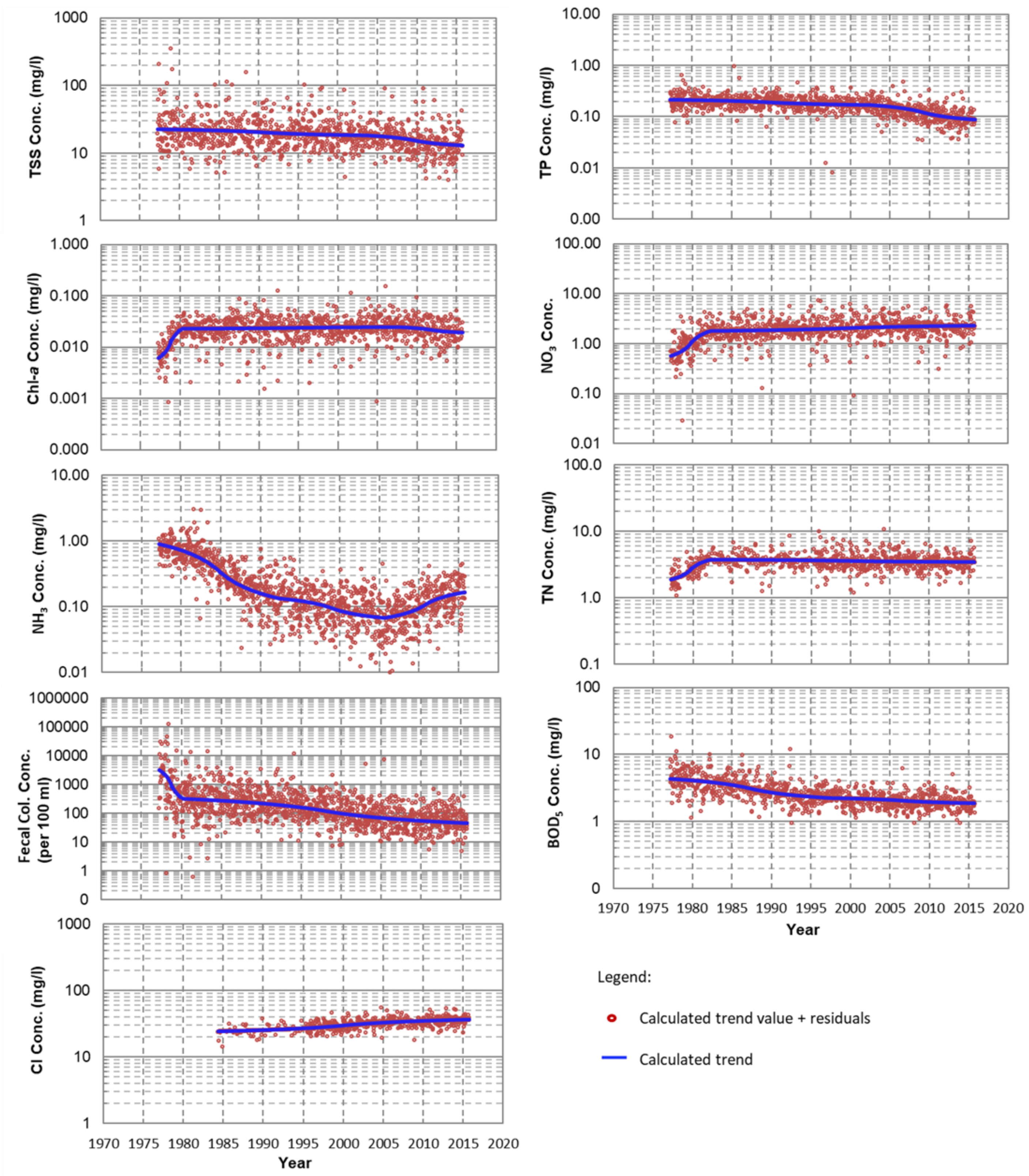
Measurements of the select water quality parameters at Grey Cloud Island (river mile 826.7) were available from 1978 to 2015, except Cl, which was available from 1985. Daily flow was estimated using USGS records at Saint Paul (USGS 05288500) plus Metropolitan WWTP discharge that was available from 1973. Because QWTREND requires a complete daily flow record for the measurement periods of water quality plus the precedent five years, water quality from 1978 and estimated daily flow from 1973 were used for trend analysis (1978 – 2015). The statistical trend results using QWTREND are presented in Table 43 and Figure 108.

Table 43: QWTREND Results for the Mississippi River at Grey Cloud Island

Parameter	Trend Period	Flow-Adjusted Concentration (mg/L)	Change (%)	Change Rate (mg/L/yr)	*p*-value	Trend
TSS	1978 – 2003	22.6 – 18.2	-19	-0.17	0.0019	⬇
	2004 – 2015	18.2 – 12.9	-29	-0.45	< 0.0001	⬇
TP	1978 – 2002	0.211 – 0.167	-21	-0.0018	0.0003	⬇
	2003 – 2015	0.167 – 0.087	-48	-0.0061	< 0.0001	⬇
Chl-*a*	1978 – 1980	0.006 – 0.023	276	0.0057	< 0.0001	⬆
	1981 – 2007	–	–	–	0.28	No trend
	2008 – 2015	0.025 – 0.020	-22	-0.00068	0.0085	⬇
NO_3	1978 – 1982	0.57 – 1.79	214	0.24	< 0.0001	⬆
	1983 – 2015	1.79 – 2.28	28	0.015	0.019	⬆
NH_3	1978 – 1992	0.908 – 0.134	-85	-0.052	< 0.0001	⬇
	1993 – 2005	0.134 – 0.068	-49	-0.0051	0.60	⬇
	2006 – 2015	0.068 – 0.167	146	0.0099	0.0013	⬆
TN	1978 – 1982	1.85 – 3.71	100	0.37	< 0.0001	⬆
	1983 – 2015	–	–	–	0.12	No trend
FC*	1978 – 1980	3236 – 323	-90	-971.0	< 0.0001	⬇
	1981 – 2015	323 – 46	-86	-7.9	< 0.0001	⬇
BOD_5	1978 – 1997	4.3 – 2.2	-48	-0.105	< 0.0001	⬇
	1998 – 2015	2.2 – 1.9	-16	-0.020	< 0.0001	⬇
Cl	1985 – 2015	24.2 – 36.3	50	0.39	< 0.0001	⬆

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 108: Water Quality Trends for the Mississippi River at Grey Cloud Island



Lock and Dam 2

Measurements of the select water quality parameters at Lock and Dam 2 (river mile 815.6) were available from 1976 to 2015, except Cl, which was available from 1985. The daily flow was measured by USGS at its Hastings station (USGS 053331580) below the Lock and Dam 2, and the records from 1971 to 2015 were used for analysis. The statistical trend results using QWTREND are presented in Table 44 and Figure 109.

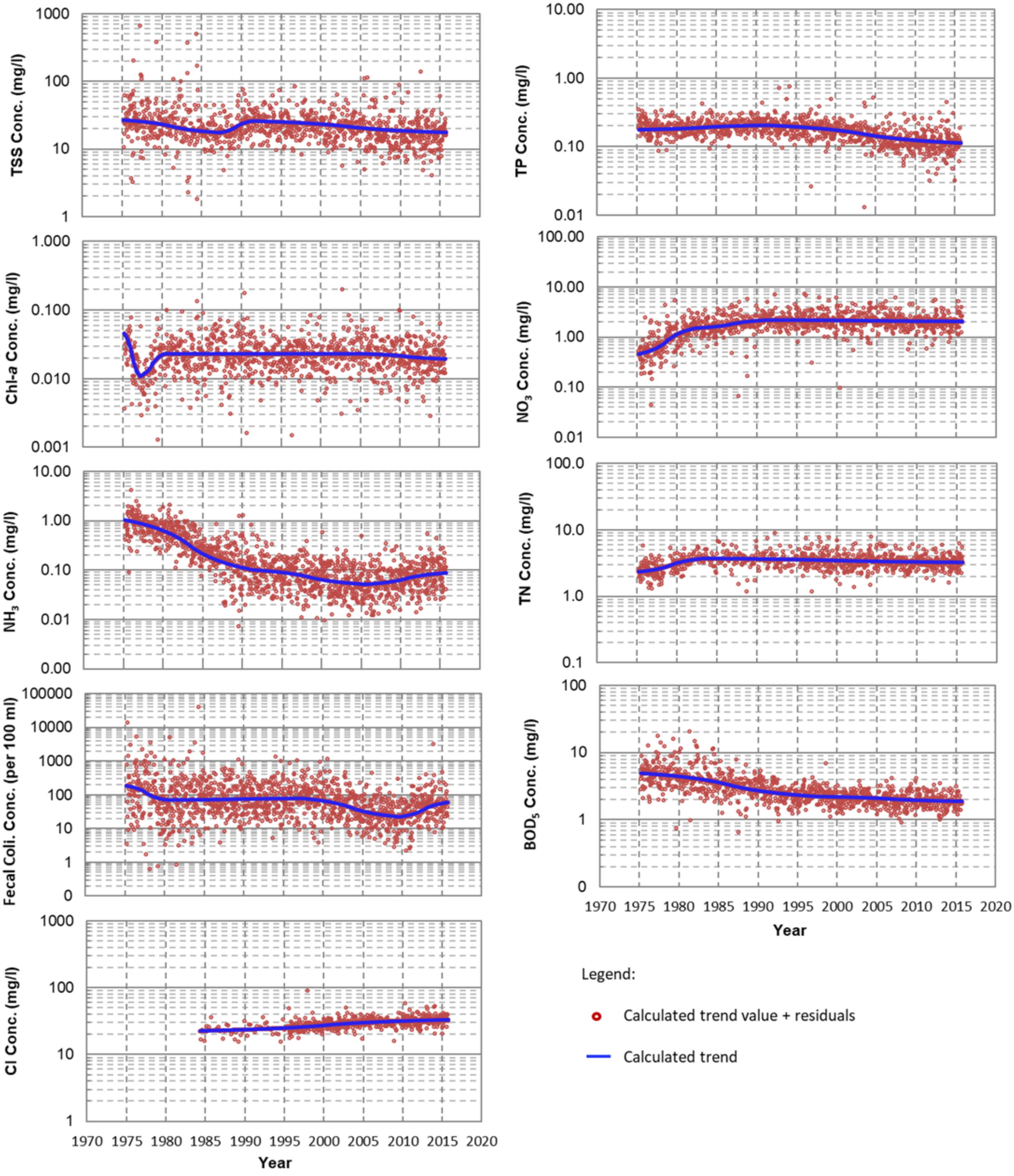
Table 44: QWTREND Results for the Mississippi River at Lock and Dam 2

Parameter	Trend Period	Flow-Adjusted Concentration (mg/L)	Change (%)	Change Rate (mg/L/yr)	*p*-value	Trend
TSS	1976 – 1987	26.6 – 17.3	-35	-0.78	0.015	⬇
	1988 – 1991	17.3 – 25.8	49	2.13	0.0004	⬆
	1992 – 2015	25.8 – 17.4	-32	-0.35	< 0.0001	⬇
TP	1976 – 1991	0.174 – 0.203	16	0.0018	0.021	⬆
	1992 – 2015	0.203 – 0.112	-45	-0.0038	< 0.0001	⬇
Chl-*a*	1976 – 1977	0.046 – 0.011	-76	-0.017	< 0.0001	⬇
	1978 – 1980	0.011 – 0.023	112	0.0040	< 0.0001	⬆
	1981 – 2005	–	–	–	0.99	No trend
	2006 – 2015	–	–	–	0.059	No trend
NO_3	1976 – 1982	0.46 – 1.50	224	0.15	< 0.0001	⬆
	1983 – 1991	1.50 – 2.17	44	0.074	0.0006	⬆
	1992 – 2015	–	–	–	0.56	No trend
NH_3	1976 – 2015	–	–	–	BRL	⬇
TN	1976 – 1983	2.34 – 3.67	57	0.17	< 0.0001	⬆
	1984 – 2015	3.67 – 3.22	-12	-0.014	0.04	⬇
FC*	1976 – 1980	186 – 71	-62	-23.0	0.0010	⬇
	1981 – 1997	–	–	–	0.54	No trend
	1998 – 2009	79 – 23	-71	-4.7	< 0.0001	⬇
	2010 – 2015	24 – 60	166	6.3	0.0002	⬆
BOD_5	1976 – 1997	4.9 – 2.2	-55	-0.12	< 0.0001	⬇
	1998 – 2015	2.2 – 1.9	-15	-0.018	0.0005	⬇
Cl	1985 – 2015	22.4 – 33.5	49	0.36	< 0.0001	⬆

BRL: Below Reporting Limit - More than 10% of measured concentrations were below the analytical report limits. QWTREND was only used for exploratory analysis to understand trend shape and direction.

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 109: Water Quality Trends for the Mississippi River at Lock and Dam 2



Lock and Dam 3

Measurements of the select water quality parameters at Lock and Dam 3 (river mile 796.9) were available from 1976 to 2015, except Cl, which was available from 1985. The daily flow was measured by USGS at its Prescott station (USGS 05344500) above the Lock and Dam 3, and the record from 1971 to 2015 was used for analysis. The statistical trend results using QWTREND are presented in Table 45 and Figure 110.

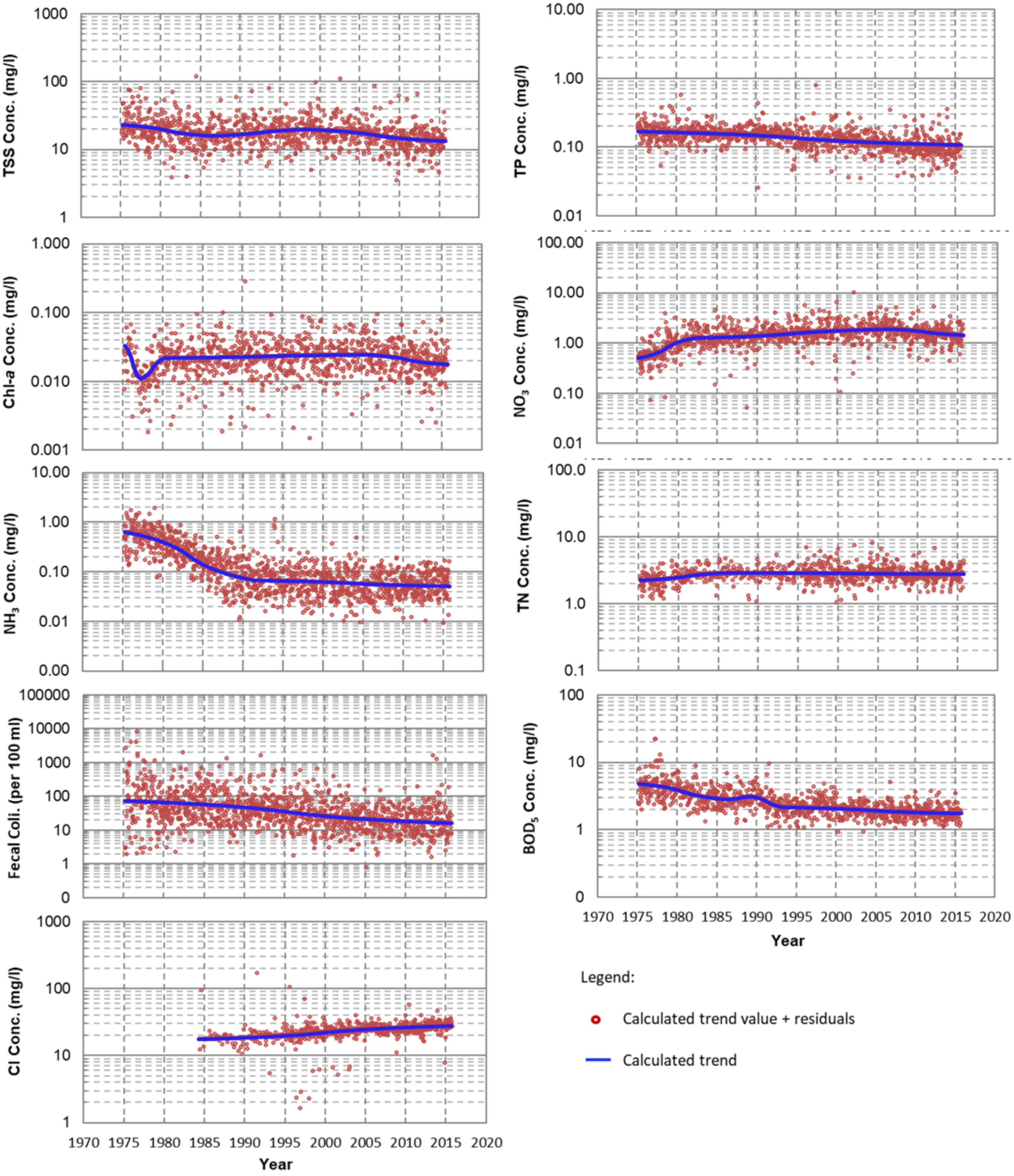
Table 45: QWTREND Results for the Mississippi River at Lock and Dam 3

Parameter	Trend Period	Flow-Adjusted Concentration (mg/L)	Change (%)	Change Rate (mg/L/yr)	*p*-value	Trend
TSS	1976 – 1986	22.8 – 15.8	-30	-0.63	< 0.0001	⬇
	1987 – 1998	15.8 – 19.6	24	0.32	< 0.0001	⬆
	1999 – 2015	19.6 – 13.3	-32	-0.37	< 0.0001	⬇
TP	1976 – 2015	0.169 – 0.106	-37	-0.0016	< 0.0001	⬇
Chl-*a*	1976 – 1977	0.033 – 0.011	-67	-0.011	< 0.0001	⬇
	1978 – 1980	0.011– 0.022	100	0.0036	< 0.0001	⬆
	1981 – 2005	–	–	–	0.13	No trend
	2006 – 2015	0.024 – 0.018	-28	-0.00067	0.0002	⬇
NO_3	1976 – 1982	0.51 – 1.26	147	0.11	< 0.0001	⬆
	1983 – 2006	1.26 – 1.87	49	0.026	< 0.0001	⬆
	2007 – 2015	1.87 – 1.43	-24	-0.049	0.0074	⬇
NH_3	1976 – 2015	–	–	–	BRL	⬇
TN	1976 – 1986	2.22 – 2.90	31	0.062	0.0001	⬆
	1987 – 2015	–	–	–	0.40	No trend
FC*	1976 – 2015	72 – 16	-77	-1.4	< 0.0001	⬇
BOD_5	1976 – 1986	4.8 – 2.8	-41	-0.18	< 0.0001	⬇
	1987 – 1989	–	–	–	0.22	No trend
	1990 – 1993	3.1 – 2.2	-30	-0.24	< 0.0001	⬇
	1994 – 2015	2.2 – 1.8	-19	-0.018	< 0.0001	⬇
Cl	1985 – 2015	17.7 – 27.5	56	0.32	< 0.0001	⬆

BRL: Below Reporting Limit - More than 10% of measured concentrations were below the analytical report limits. QWTREND was only used for exploratory analysis to understand trend shape and direction.

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 110: Water Quality Trends for the Mississippi River at Lock and Dam 3



Minnesota River

Jordan (MI 39.4)

For the Minnesota River at Jordan (river mile 39.4), the following measurements of water quality were available for trend analysis:

- TSS, FC, and BOD_5 from 1976 to 2015
- TP, NO_3, NH_3, Chl-*a* from 1979 to 2015
- TN from 1980 to 2015
- Cl from 1985 to 2015

The daily flow was measured by USGS at its Jordan station (USGS 05330000), and the record from 1971 to 2015 was used for analysis. The statistical trend results using QWTREND are presented in Table 46 and Figure 111.

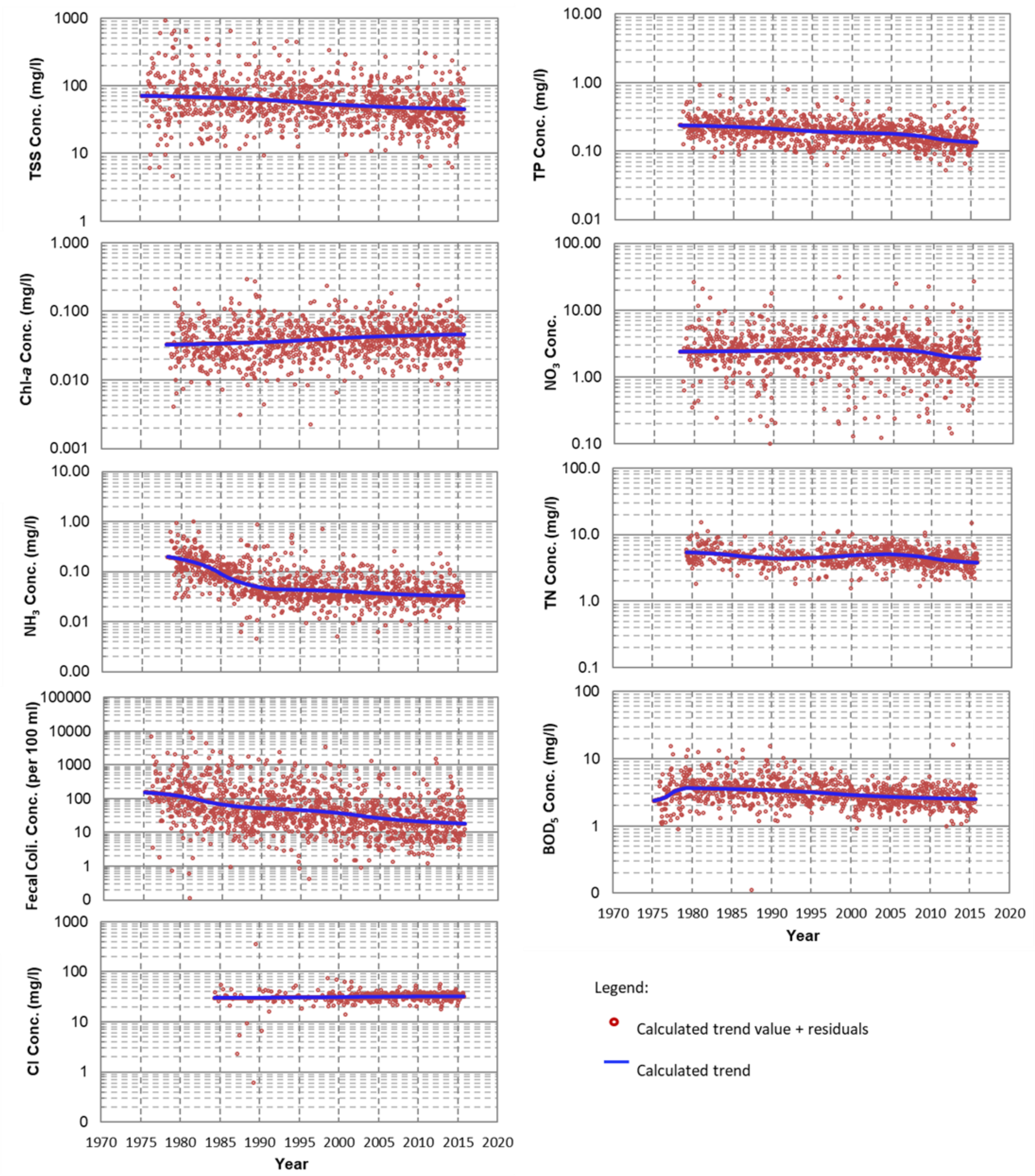
Table 46: QWTREND Results for the Minnesota River at Jordan

Parameter	Trend Period	Flow-Adjusted Concentration (mg/L)	Change (%)	Change Rate (mg/L/yr)	*p*-value	Trend
TSS	1976 – 2015	71.0 – 44.8	-37	-0.65	< 0.0001	⬇
TP	1979 – 2004	0.24 – 0.18	-24	-0.0022	< 0.0001	⬇
	2005 – 2015	0.18 – 0.13	-26	-0.0042	< 0.0001	⬇
Chl-*a*	1979 – 2015	0.033 – 0.046	39	0.00035	0.0013	⬆
NO_3	1979 – 2004	–	–	–	0.48	–
	2005 – 2015	2.61 – 1.87	-28	-0.067	0.012	⬇
NH_3	1976 – 2015	–	–	–	BRL	⬇
TN	1980 – 1991	5.38 – 4.36	-19	-0.086	0.023	⬇
	1992 – 2004	4.36– 5.05	16	0.053	0.049	⬆
	2005 – 2015	5.05 – 3.81	-24	-0.11	0.0005	⬇
FC*	1976 – 1989	155 – 53	-66	-7.3	< 0.0001	⬇
	1990 – 2015	53 – 18	-66	-1.3	< 0.0001	⬇
BOD_5	1976 – 1979	2.35 – 3.70	57	0.34	0.0002	⬆
	1990 – 2015	3.70 – 2.49	-33	-0.034	< 0.0001	⬇
Cl	1985 – 2015	29.8 – 32.4	8	0.081	0.036	⬆

BRL: Below Reporting Limit - More than 10% of measured concentrations were below the analytical report limits. QWTREND was only used for exploratory analysis to understand trend shape and direction.

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 111: Water Quality Trends for the Minnesota River at Jordan



Fort Snelling (MI 3.5)

Measurements of the select water quality parameters at Fort Snelling (river mile 3.5) were available for from 1976 to 2015, except Cl, which was available from 1985. The daily flow was measured by USGS at its Fort Snelling station (USGS 05330920), and the record from 1971 to 2015 was used for analysis. The statistical trend results using QWTREND are presented in Table 47 and Figure 112. No statistically significant trend models were found for Cl because modeled statistic index of AIC value was larger than initial AIC for the assessment period (1985 – 2015).

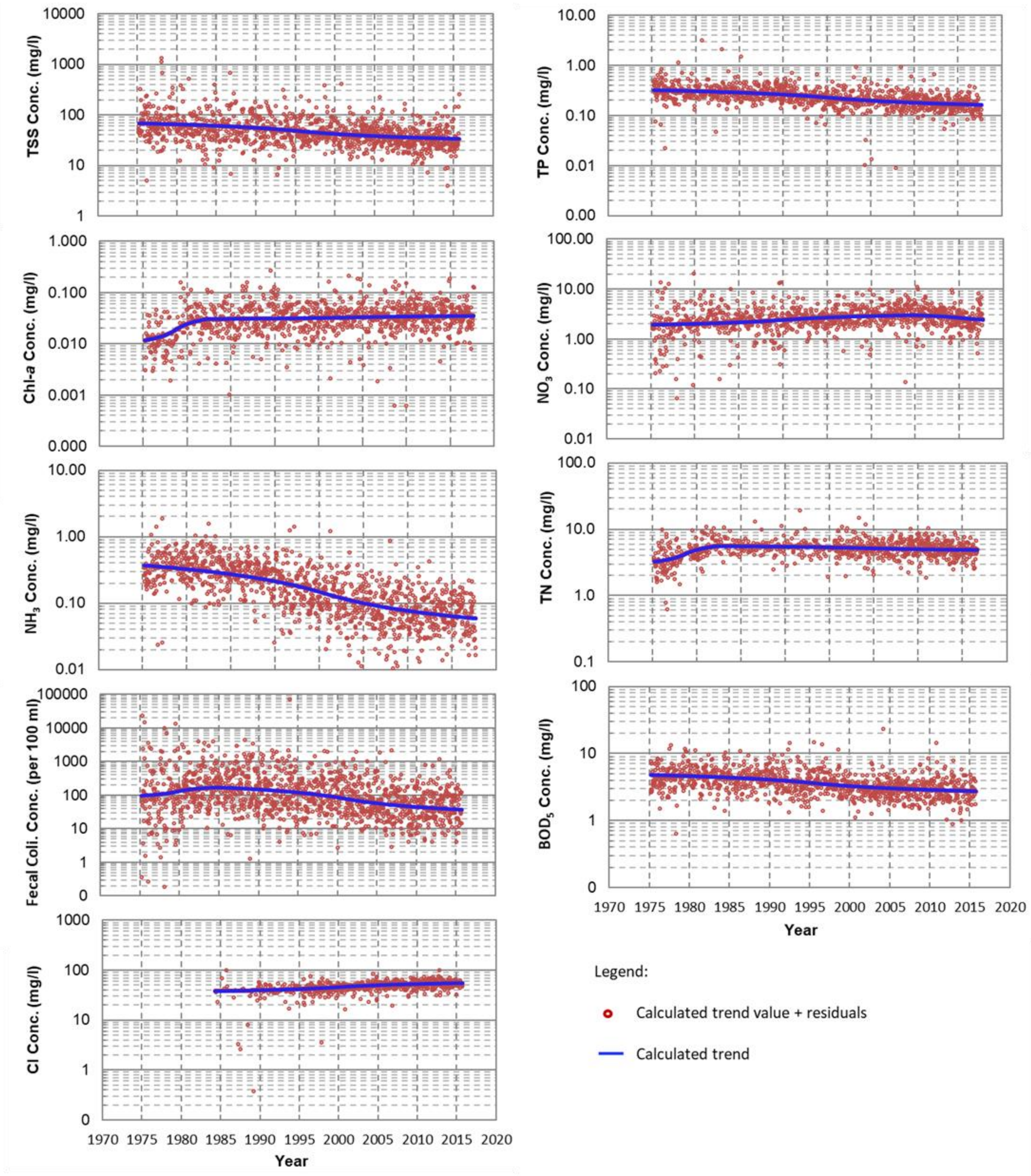
Table 47: QWTREND Results for the Minnesota River at Fort Snelling

Parameter	**Trend Period**	**Flow-Adjusted Concentration (mg/L)**	**Change (%)**	**Change Rate (mg/L/yr)**	***p*-value**	**Trend**
TSS	1976 – 2015	67.9 – 33.4	-51	-0.86	< 0.0001	⬇
TP	1976 – 2015	0.321 – 0.158	-51	-0.0041	< 0.0001	⬇
Chl-*a*	1976 – 1982	0.012 – 0.030	162	0.0027	< 0.0001	⬆
	1983 – 2015	–	–	–	0.16	No trend
NO_3	1976 – 2004	1.93 – 3.01	56	0.037	<0.0001	⬆
	2005 – 2015	3.01 – 2.33	-22	-0.061	0.034	⬇
NH_3	1976 – 2015	–	–	–	BRL	⬇
TN	1976 – 1982	3.22 – 5.62	74	0.34	<0.0001	⬆
	1983 – 2015	5.62 – 4.88	-13	-0.023	0.032	⬇
FC*	1976 – 1984	96 – 169	76	8.1	0.037	⬆
	1985 – 2015	169 – 37	-78	-4.2	<0.0001	⬇
BOD_5	1976 – 2015	4.75 – 2.72	-43	-0.051	< 0.0001	⬇
Cl	1985 – 2015	–	–	–	–	No trend

BRL: Below Reporting Limit - More than 10% of measured concentrations were below the analytical report limits. QWTREND was only used for exploratory analysis to understand trend shape and direction.

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 112: Water Quality Trends for the Minnesota River at Fort Snelling



St. Croix River

Stillwater (SC 23.3)

Measurements of the select water quality parameters at Stillwater (river mile 23.3) were available from 1976 to 2015, except Cl, which was available from 1985.The daily flow was measured by USGS at its Stillwater station (USGS 05341550), and the record from 1971 to 2015 was used for analysis. The statistical trend results using QWTREND are presented in Table 48 and Figure 113.

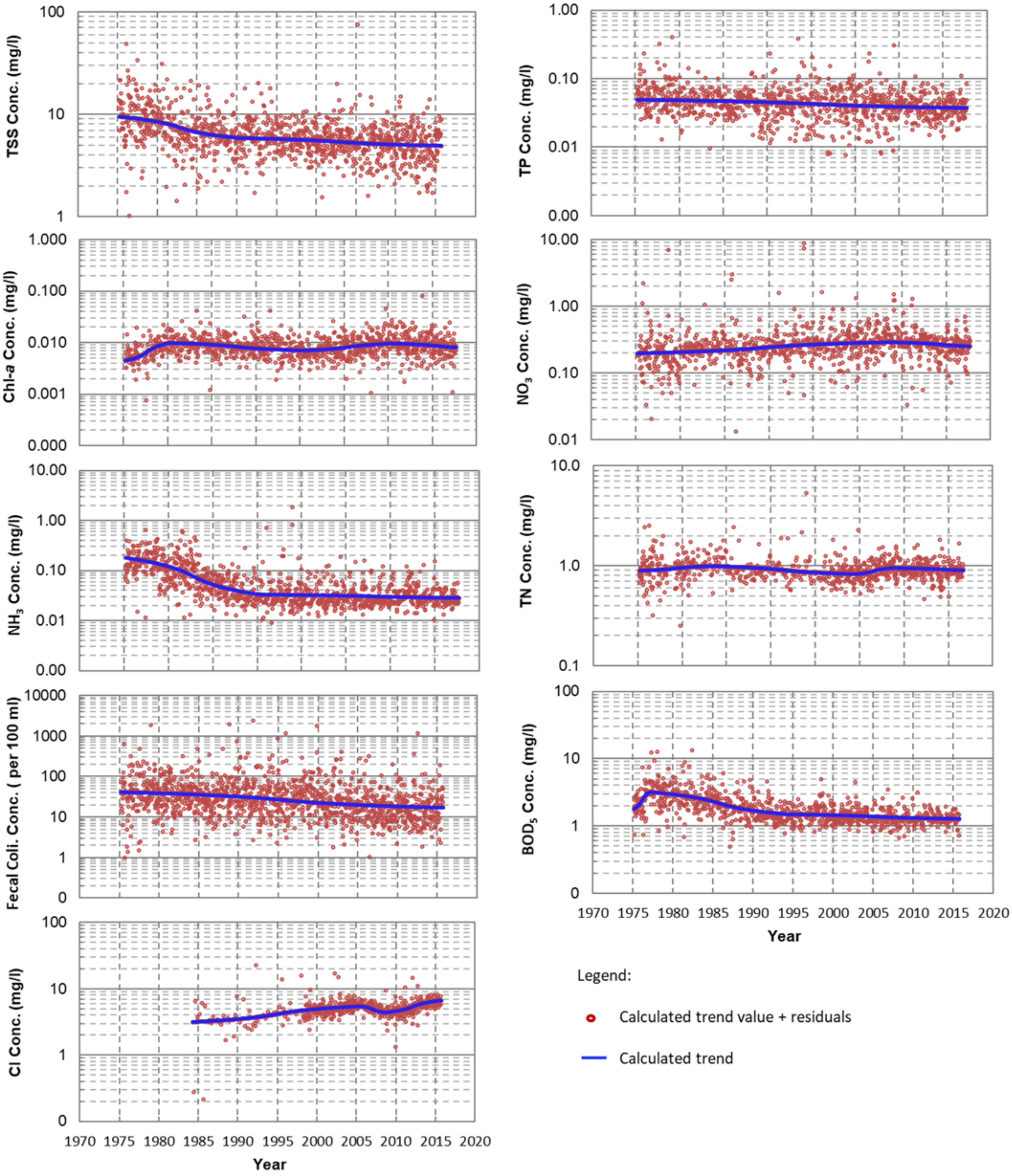
Table 48: QWTREND Results for the St. Croix River at Stillwater

Parameter	Trend Period	Flow-Adjusted Concentration (mg/L)	Change (%)	Change Rate (mg/L/yr)	*p*-value	Trend
TSS	1976 – 1990	9.5 – 5.9	38	-0.24	<0.0001	⬇
	1991 – 2015	5.9 – 4.9	-16	-0.037	0.0002	⬇
TP	1976 – 2015	0.049 – 0.037	-26	-0.00032	< 0.0001	⬇
Chl-*a*	1976 – 1980	0.004 – 0.010	119	0.0011	< 0.0001	⬆
	1981 – 1995	0.010 – 0.007	-28	-0.00019	< 0.0001	⬇
	1996 – 2005	0.007 – 0.010	36	0.00026	< 0.0001	⬆
	2006 – 2015	0.010 – 0.008	-20	-0.00019	0.023	⬇
NO_3	1976 – 2003	0.20 – 0.29	48	0.0034	<0.0001	⬆
	2004 – 2015	0.29 – 0.24	-16	-0.0039	0.028	⬇
NH_3	1976 – 2015	–	–	–	BRL	⬇
TN	1976 – 2015	–	–	–	0.082	No trend
FC*	1976 – 2015	41 – 17	-59	-0.6	< 0.0001	⬇
BOD_5	1976 – 2015	–	–	–	BRL	⬇
Cl	1985 – 2005	3.1 – 5.4	72	0.11	<0.0001	⬆
	2006 – 2008	5.4 – 4.3	-20	-0.35	0.0006	⬇
	2009 – 2015	4.3 – 6.6	52	0.32	<0.0001	⬆

BRL: Below Reporting Limit - More than 10% of measured concentrations were below the analytical report limits. QWTREND was only used for exploratory analysis to understand trend shape and direction.

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 113: Water Quality Trends for the St. Croix River at Stillwater



Prescott (SC 0.3)

Measurements of the select water quality parameters at Prescott (river mile 0.3) were available from 1976 to 2015, except Cl, which was available from 1985. The daily flow was measured by USGS at its Prescott station (USGS 05344490), and the record from 1971 to 2015 was used for analysis. The statistical trend results using QWTREND are presented in Table 49 and Figure 114.

Table 49: QWTREND Results for the St. Croix River at Prescott

Parameter	Trend Period	Flow-Adjusted Concentration (mg/L)	Change (%)	Change Rate (mg/L/yr)	*p*-value	Trend
TSS	1976 – 1985	8.4 – 3.1	-63	-0.53	<0.0001	⬇
	1986 – 1994	3.1 – 3.8	24	0.082	0.0005	⬆
	1995 – 2015	3.8 – 2.1	-45	-0.082	<0.0001	⬇
TP	1976 – 1996	0.051 – 0.028	-46	-0.0011	< 0.0001	⬇
	1997 – 1998	0.028 – 0.040	45	0.0062	< 0.0001	⬆
	1999 – 2008	0.040 – 0.028	-31	-0.0012	0.0003	⬇
	2009 – 2015	0.028 – 0.035	26	0.0010	0.041	⬆
Chl-*a*	1976 – 1980	0.005 – 0.009	94	0.00089	0.0005	⬆
	1981 – 1996	0.009 – 0.007	-26	-0.00015	0.0069	⬇
	1997 – 2005	0.007 – 0.010	49	0.00037	0.0003	⬆
	2006 – 2015	–	–	–	0.066	No trend
NO_3	1976 – 2015	0.35 – 0.58	67	0.0058	< 0.0001	⬆
NH_3	1976 – 2015	–	–	–	BRL	⬇
TN	1976 – 1982	0.92 – 1.10	-19	0.025	<0.0001	⬆
	1983 – 2015	1.10 – 1.20	-10	0.0033	0.0010	⬆
FC*	1976 – 2015	–	–	–	BRL	⬇
BOD_5	1994 – 2015	–	–	–	BRL	⬇
Cl	1985 – 2004	3.5 – 6.4	83	0.14	<0.0001	⬆
	2005 – 2010	6.4 – 5.0	-22	-0.24	<0.0001	⬇
	2011 – 2015	5.0 – 8.5	71	0.71	<0.0001	⬆

BRL: Below Reporting Limit - More than 10% of measured concentrations were below the analytical report limits. QWTREND was only used for exploratory analysis to understand trend shape and direction.

* Unit: organisms/100 mL for concentration and organisms/100 mL/yr for change rate

Figure 114: Water Quality Trends for the St. Croix River at Prescott