

Report on the State of the Lake

Assessing Lake St. Croix in 2018 On the Way to the 2020 TMDL Goals

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EXECUTIVE SUMMARY

Located at the confluence of the St. Croix River with the Mississippi River, Lake St. Croix serves as the integrator of a 7,760 square-mile drainage area, which includes eastern portions of the burgeoning Twin Cities Metropolitan Area. Lake St. Croix comprises the lower 25 miles of the St. Croix River, forming part of the boundary between Minnesota and Wisconsin.

The “State of the Lake Report—Assessing Lake St. Croix in 2018” entails a comprehensive assessment of the ecological status and trends of the lake from 1999 through 2015. The primary impetus for this report was the observation by Lafrancois et al. (2009) that chlorophyll *a* produced by algae in the lake seems to have de-coupled from the limiting nutrient phosphorus. Since 1976, total phosphorus concentrations have declined by 0.2 µg/L per year, but chlorophyll *a* concentrations have not declined according to a seasonal Kendall trend test. The mechanism for this decoupling is not yet clearly understood. Another key impetus for this report is a looming resource management goal set by the St. Croix Basin Water Resources Planning Team (hereafter, Basin Team) to improve the ecological health of Lake St. Croix. In 2006, the States of Wisconsin and Minnesota signed an agreement to reduce phosphorus loading to Lake St. Croix by 20% by the year 2020, which became the basis for an interstate Total Maximum Daily Load (TMDL) Project, accepted by the U.S. Environmental Protection Agency in 2012 (MPCA & WDNR 2012). The purpose of this assessment report is to determine whether, given the decoupling between phosphorus and chlorophyll *a*, it is likely that Lake St. Croix will meet the TMDL targets by 2020.

The Lake St. Croix TMDL Report (MPCA & WDNR 2012) detailed a plan to achieve the reduction in phosphorus loading to Lake St. Croix, from 460 metric tons/year in the 1990s to 360 metric tons/year. This reduction is necessary to restore the ecological health status of Lake St. Croix based on summer (June-September) means measured at the lake surface for the following criteria: 1) Secchi depth clarity greater than 1.4 meters, 2) total phosphorus concentrations below 40 µg/L, and 3) viable chlorophyll *a* concentrations below 14 µg/L. These conditions occurred in Lake St. Croix in the 1940s, prior to the dominance of algal communities by floating phytoplankton, including blue-green algae that can lead to abundant or even toxic algal blooms. The historical conditions in Lake St. Croix were determined from decadal means measured in lake sediment cores analyzed by Triplett et al. (2009). Therefore, the final criteria for achieving the TMDL goal is decadal means of the annual loads and summer concentrations that are listed above.

Lake St. Croix is a rare hydrologic feature: a riverine lake. The outlet of the St. Croix River is naturally dammed by glacial-era sediments, and confined to a narrow channel at Prescott, WI, where it joins the Mississippi River. The result of that narrow constraint is a deep, elongate lake between Stillwater, MN and Prescott, WI, through which the river constantly flows. In addition, three tributaries flowing into Lake St. Croix have deposited large deltas, creating three narrow pinch points that delineate the four separate pools of Lake St. Croix. Pool 1 runs from Stillwater to the outlet of the Willow River, Pool 2 runs from below the Willow River to the outlet of Valley Creek, Pool 3 runs from Valley Creek to the outlet of the Kinnickinnic River, and Pool 4 runs from the Kinnickinnic River to the lake outlet at Prescott.



There are several hydrologic and ecological factors that drive the observed patterns in Lake St. Croix water quality. The key drivers and their observations are as follows:

Driver I: Elongated Water Body

The dominant inflow at Stillwater, combined with the elongated shape of Lake St. Croix, creates a longitudinal pattern between two endpoints in Lake St. Croix: 1) turbid river-like conditions at Stillwater, and 2) clear lake-like conditions at Prescott. At Stillwater, there is low clarity, high phosphorus, and high algae concentrations. At Prescott, there is high clarity, low phosphorus, and low algae concentrations. The transition within Lake St. Croix, between river-like conditions and lake-like conditions, typically occurs in the middle of Pool 2.

Driver II: Seasonality of Temperature and Hydrology

The upper Midwestern extremes, of cold winters and hot summers, translate into annual cycles of water quality within Lake St. Croix. The low flows of winter carry few sediments and nutrients, and few species of algae grow at this time. Warming temperatures in April release a winter worth of snowmelt, carrying high sediment and nutrient loads, exceeding water quality standards and enabling the growth of springtime algae. In July and August, during the hottest part of the year and when river flow is at its lowest level of the growing season, algae growth and chlorophyll *a* concentrations reach their maximum for the year, often generating toxic blooms at this time. October and November rain storms bring in the last flush of sediments and nutrients prior to the winter slowdown.

Driver III: Lake Stratification

By the heat of July, Lake St. Croix has stratified. The warm surface layer prevents the cold bottom layer from accessing atmospheric oxygen, and excess total phosphorus is released into the cold bottom layer. As temperatures start cooling in September, the phosphorus-rich bottom waters become fully mixed with the lake surface.

Driver IV: High Flows and Low Flows Alternate in Nearly Decadal Cycles

During low-flow periods, the monitoring sites of Lake St. Croix showed increased clarity, decreased phosphorus, and increased chlorophyll *a*, compared to decreased clarity, increased phosphorus, and decreased chlorophyll *a* during high-flow periods. Lake water clarity and phosphorus concentrations improved during the relative calmness of low-flow conditions, but those same conditions allow for abundant algal growth. On the other hand, high-flow conditions deliver muddy waters that carry phosphorus to the lake but reduce clarity to the extent that inhibits light penetration and growth of algae.

Combined Effects of Drivers:

The seasonal differences in water quality between sampling sites at Stillwater and Prescott are informative:

- Total suspended solids (TSS) and total phosphorus (TP) peaked in summer at Stillwater but peaked in spring and autumn at Prescott.

- Viable chlorophyll *a* (VChla) was usually higher during low-flow conditions than during high-flow conditions.
- Excess TP concentrations at Prescott in October and November most likely result from mixing after lake de-stratification.

Other differences in water quality patterns were also observed between sampling sites at Stillwater and Prescott:

- The highest concentrations of TSS, TP, and VChla occur at Stillwater where basin runoff enters Lake St. Croix; concentrations are much lower where Lake St. Croix flows into the Mississippi River at Prescott.
- The “turbid river” site at Stillwater had higher concentrations of TSS, TP, and VChla during low-flow conditions, compared to high-flow conditions.
- The “clear lake” site at Prescott had higher concentrations of TSS and VChla, but slightly lower concentrations of TP, during low-flow conditions compared to high-flow conditions.

Conclusions

The Lake St. Croix TMDL water quality standards for summer means (Clarity = 1.4 m, TP = 40 µg/L, and VChla = 14 µg/L) are intended to create an ecological state last seen in Lake St. Croix in the 1940s: a clear lake dominated by bottom-dwelling algae. Currently (2018), Lake St. Croix is dominated by floating algae, including blue-green algae that can produce toxic blooms.

Lowest Water Quality is Where Basin Runoff Enters Lake St. Croix

While there is evidence of excess phosphorus and algae throughout the length of the lake, the largest concentrations occur at Stillwater where basin runoff enters Lake St. Croix. In contrast, water quality improves downstream toward Prescott. Lake St. Croix functions well as a sediment (and sediment-borne nutrient) trap, but likely has specific, limited capability in ecological functioning. The difference between the decadal mean VChla concentrations at the two endpoints, in any given year, ranges from 9-12 µg/L. The highs and lows at Prescott (and through the whole lake) follow the highs and lows at Stillwater. This would point to a further need to investigate the sources of degraded water quality immediately upstream of Stillwater.

Water Residence Time and Algal Blooms Vary Inversely with Flow

The observation that phosphorus and chlorophyll *a* concentrations vary inversely with flow condition points to a potential ecological mechanism for the decoupling of algae from nutrient supply. That is, in the presence of sufficient nutrients, algal growth rates scale with flow-dependent factors in aquatic plant growth, most likely light penetration and water residence time. High flows carry high phosphorus concentrations, but turbid water clouded by suspended solids and high dissolved organic carbon (DOC) concentrations shades the photic zone, and algae is transported downstream before it reproduces. In contrast, low flows carry lower (but sufficient) phosphorus concentrations for high algal productivity in sluggish, but clear waters. Cyanobacteria (blue-green algae) are particularly well-suited to the low-flow conditions because they can control their buoyancy to navigate downward into the phosphorus-rich waters below the thermocline and return back up to light in the photic zone.



Looking Beyond 2020

Data presented in this report indicate that the 2020 TMDL goals will be challenging to meet because of wet and dry cycles, as well as spatial and temporal variability in the following factors: internal loading of total phosphorus, clarity, and algae – all of which are challenging to manage in the watershed. The temporal decline in phosphorus concentrations is promising, but the desired ecological response of reduced phytoplankton abundance likely will not occur by 2020. Through data analytics and lake modeling, we are gaining a better understanding of the relationship between phosphorus and chlorophyll *a* in Lake St. Croix. However, climate change may alter that relationship through changes in flows, watershed loads, and lake thermal regimes. Therefore, it is important to continue monitoring flows and water quality in Lake St. Croix.

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DEDICATION

Deepest gratitude goes to Jim and Roberta Harper, of Harper Consulting, Inc., who have steadfastly weathered wind, rain, and a barge or two, to bring us high quality lake monitoring data for over ten years. They have been once-in-a-lifetime citizen scientists who were instrumental in furthering the understanding of Lake St. Croix ecology. This work is happily dedicated to them.

ABBREVIATIONS

cfs	cubic feet per second, volumetric discharge rate
Chla	chlorophyll <i>a</i>
degF	degree Fahrenheit
DOC	dissolved organic carbon
DP	dissolved phosphorus
in	inches
km	kilometer
MCES	Metropolitan Council Environmental Services
MN	Minnesota
MPCA	Minnesota Pollution Control Agency
MWA	Moving Window Average, temporal average assigned to centroid of period window
NPS	National Park Service
Qw	river discharge (cfs)
SC	specific conductance ($\mu\text{S}/\text{cm}$)
SCWRS	St. Croix Watershed Research Station
SMM	Science Museum of Minnesota
TMDL	total maximum daily load, pollution limit
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VChla	viable chlorophyll <i>a</i> , pheophyton-corrected
WDNR	Wisconsin Department of Natural Resources
WI	Wisconsin

INTRODUCTION

Lake St. Croix is a rare hydrologic feature: a riverine lake. The outlet of the St. Croix River is naturally dammed by glacial-era sediments, and confined to a narrow channel at Prescott, WI, where it joins the Mississippi River. The result of that narrow constraint is a deep, elongated lake within the river valley between Stillwater, MN and Prescott, WI, through which the river constantly flows. The St. Croix Basin Water Resources Planning Team (hereafter, Basin Team) has always been interested in the ecological health of Lake St. Croix because it integrates human activities across the entire basin upstream of the lake.

The Need for Assessment

When the construction of the new St. Croix Crossing bridge was approved, the Basin Team had the opportunity to decide how to apportion the funds appropriated for environmental mitigation. The members of the Basin Team's Monitoring & Assessment (M&A) Committee have placed a high priority on the pursuit of environmental assessment projects, especially those that integrate data across agencies. A persistent problem for Lake St. Croix monitoring is that volumes of high-quality data are being collected without assessment or synthesis across monitoring agencies. Therefore, Lake St. Croix was chosen by the M&A Committee for an assessment pilot project, as a precursor for a future goal of a comprehensive basin-wide assessment. Ultimately, the Basin Team rated a State of the Lake Report among the highest priority proposals for bridge mitigation funding.

In the history of water-resources management of the St. Croix Basin, there has been only one assessment project that synthesized data from several major and complementary monitoring efforts: this synthesis was the basis for the 100 metric tons phosphorus reduction goal (Davis 2004). Twenty years have passed since collection of the data that generated the reduction goal, which is set for 2020, just about one year from now. There is a need for a timely follow-up assessment to determine progress toward the 2020 goal.

Location and Setting

Located at the confluence of the St. Croix River with the Mississippi River (Figure 1), Lake St. Croix serves as the integrator of a 7,760 square mile drainage area. Lake St. Croix comprises the lower 25 miles of the St. Croix River, forming part of the boundary between Minnesota and Wisconsin.

Three major tributaries flowing into Lake St. Croix have deposited large deltas, creating three narrow pinch points that delineate the four separate pools of Lake St. Croix. Pool 1 runs from Stillwater to the outlet of the Willow River, Pool 2 runs from below the Willow River to the outlet of Valley Creek, Pool 3 runs from below Valley Creek to the outlet of the Kinnickinnic River, and Pool 4 runs from below the Kinnickinnic River to the lake outlet at Prescott. The dimensions of the four pools are listed in Table 1. Pool 1 is the longest yet shallowest pool and receives the bulk of human-caused inputs to the lake. Pool 2 is the widest pool and deeper than Pool 1, thus allowing for wind mixing within this pool. Pools 3 and 4 are both narrow yet deep, dropping off to 70 and 60 feet, respectively, on their upstream ends.

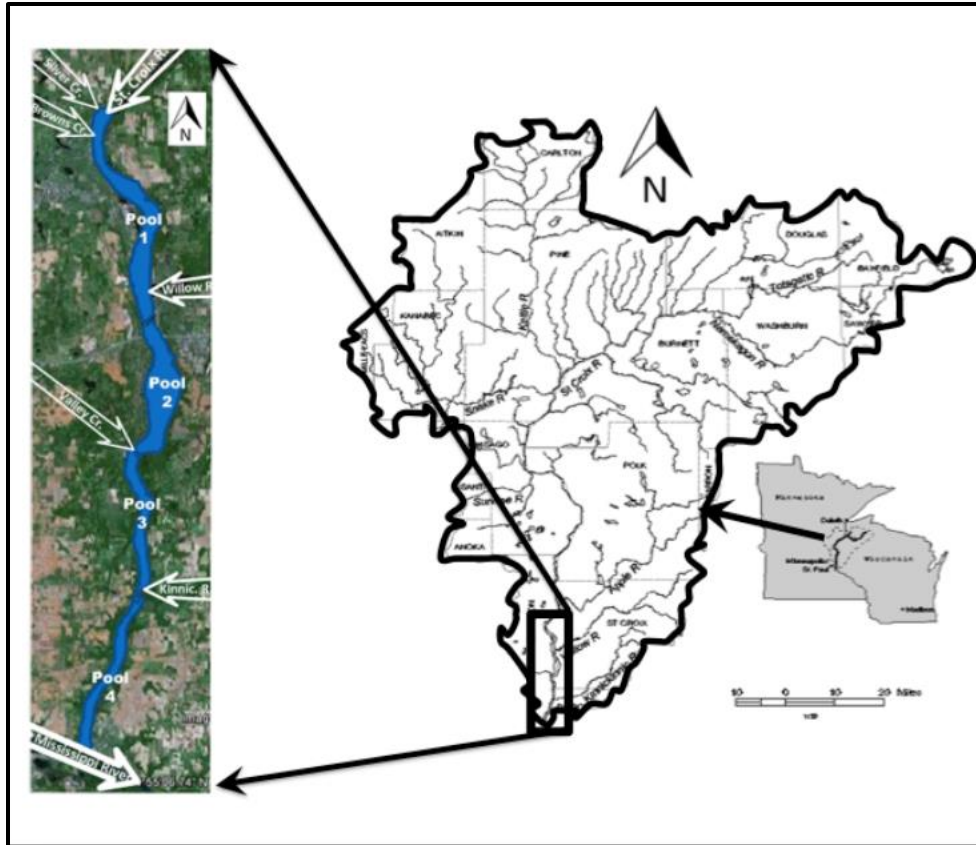


Figure 1. Location of Lake St. Croix and major surface inflows (white arrows) to Lake St. Croix, including the mainstem St. Croix River above Stillwater, MN, direct tributaries to the four pools, and outflow below Prescott, WI to the Mississippi River.

Table 1. Dimensions of the four pools of Lake St. Croix.

Pool (number and name)	Length (mi)	Area (sq. mi)	Avg. Depth (ft)
1 – Bayport Pool	8.3	4.4	20
2 – Troy Beach Pool	5.1	4.9	33
3 – Black Bass Pool	5.0	2.1	46
4 – Kinnickinnic Pool	5.6	2.2	33

Previous Efforts to Assess Lake St. Croix

The phosphorus reduction goal (Davis 2004) was determined by comparing historical conditions recorded in lake sediment cores (Triplett et al. 2003) with existing 1998-1999 monitoring data (Lenz et al. 2003) and future projections from a BATHTUB lake model (Robertson and Lenz 2002). The lake cores indicated that the dominance of planktic diatoms (floating near the water surface) in Lake St. Croix is a recent phenomenon; prior to 1950, the lake was dominated by benthic (living near the lake bottom) diatom communities, which require a high degree of water clarity (Figure 2). The inflow loading of total phosphorus in the 1940s was 360 metric tons per year, compared to 460 metric tons per year since 1980 (Figure 3). The future projections by the

lake model indicated that the current trend was toward greater eutrophication of Lake St. Croix unless action was taken to alter that trajectory (Davis 2004). Thus, the Basin Team created the phosphorus reduction goal of 100 tons per year, aiming to achieve 360 tons per year by 2020.

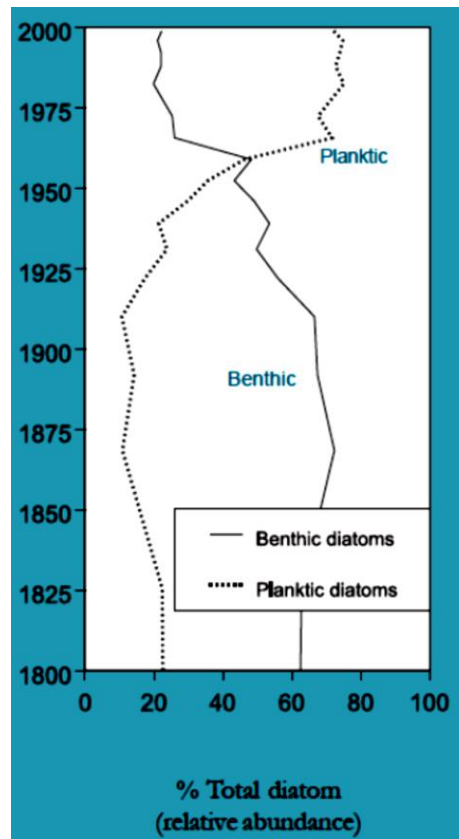


Figure 2. Relative abundance (% of total) of planktic and benthic diatom species measured in Lake St. Croix sediment cores per year from 1800 to 2000 (from Davis 2004).

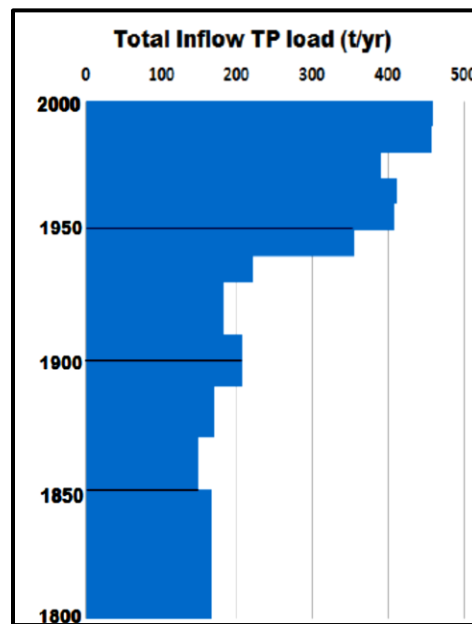


Figure 3. Historical loading of total phosphorus (TP) in the sum of all Lake St. Croix inflows, in metric tons per year (t/yr), from 1800 to 2000, estimated from in-lake sedimentation measured in lake cores and diatom-inferred outflow concentrations (from Triplett et al. 2003).

In 2006, agency commissioners of Wisconsin Department of Natural Resources (WDNR) and Minnesota Pollution Control Agency (MPCA) signed an agreement to reduce phosphorus loading to Lake St. Croix by 20% by the year 2020, which became the basis for an interstate Total Maximum Daily Load (TMDL) Project. Lake St. Croix was subsequently documented to exceed three site-specific water quality standards (clarity, phosphorus, and chlorophyll *a*) and in 2009 was added to the Minnesota and Wisconsin 303(d) lists of impaired waters for eutrophication because of excess nutrients and algae. The Lake St. Croix TMDL Report (MPCA & WDNR 2012) detailed a plan to reduce phosphorus loading to Lake St. Croix to the ecological conditions of the 1940s and reduce annual phosphorus loads by 100 tons. This reduction is necessary to restore Lake St. Croix to an ecological health status with the following criteria: summer (June-September) means measured at the lake surface of: 1) Secchi depth clarity greater than 1.4 meters, 2) total phosphorus concentrations below 40 µg/L, and 3) chlorophyll *a*

concentrations below 14 µg/L. The historical conditions in Lake St. Croix were determined from decadal means measured in lake sediment cores (Figure 3). Therefore, the final criteria for achieving the TMDL goal is decadal means of the annual loads and summer concentrations that are listed above.

A recent study of water quality in Lake St. Croix by Lafrancois et al. (2009) questioned whether assumptions about the lake ecology were correct: will reduced nutrients result in reduced algae as measured by chlorophyll *a*? Since 1976, Kendall trend tests indicate total phosphorus concentrations have declined by 0.2 µg/L per year, but chlorophyll *a* concentrations have not declined during the same period (Figure 4). The mechanism for this decoupling is not yet clearly understood but is most likely the result of internal loading from phosphorus storage in the lake sediments. The U.S. Geological Survey (USGS) recently published an updated longitudinal lake model that can calculate more variables associated with nutrient cycling within Lake St. Croix compared to previous models (Smith et al., 2018), providing more accurate projections under climate change.

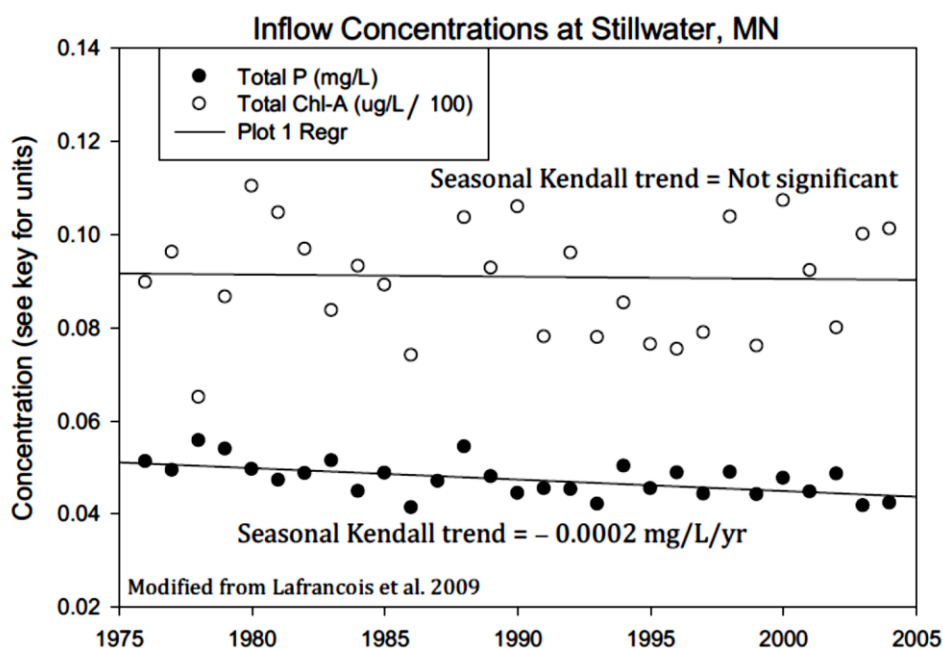


Figure 4. Seasonal Kendall trend test results for inflow total phosphorus (P) and total chlorophyll *a* (Chla) concentrations for the St. Croix River monitoring site at Stillwater, MN (1976-2004).

Table 2 contains a compilation of previous efforts to assess the ecological health functioning within Lake St. Croix, starting in the late 1990s, including efforts to characterize the influence of the Wisconsin and Minnesota tributaries that flow directly into Lake St. Croix. Since 1999, Metropolitan Council Environmental Services (MCES) has monitored and calculated monthly and annual loads for three tributaries, Browns, Silver, and Valley creeks (Metropolitan Council Environmental Services 2018). Finally, the USGS conducted three years (2012- 2014) of loading analysis on the Willow and Kinnickinnic Rivers (Ben Torrison, USGS, written commun., 2018).

Table 2. Compilation of previous efforts to assess the ecological health functioning within Lake St. Croix, including a brief description and listing of resulting publications.

Year(s)	Description	Publications
1997-2001	Interagency collaborative research led by the Basin Team into phosphorus mass balance, watershed loading, historical point source loading, and lake sediment coring.	Robertson and Lenz (2002), Lenz et al. (2003), Edlund et al. (2009 a & b), Triplett et al. (2009)
2002-2004	Basin Team compiled data and used to derive a goal of a 20% reduction in phosphorus inputs to Lake St. Croix by 2020, designed to achieve benthic dominance in algal communities.	Davis (2004)
2005-2008	Trend analysis of flows and nutrient concentrations and loads at Lake St. Croix inflow and outflow, 1976-2004. This study identified the decoupling between the nutrient phosphorus and the resulting algal production of chlorophyll <i>a</i> .	Lafrancois et al. (2009)
2006	WDNR and MPCA agency commissioners sign nutrient reduction agreement.	
2007-2009	Lake St. Croix Total Phosphorus Loading Study, laid the groundwork for basin-wide phosphorus loading information needed for an anticipated TMDL project.	Lafrancois et al. (2009)
2010	Impaired Waters 303(b) Listing for Lake St. Croix, due to eutrophication from excess phosphorus.	
2010-2012	Lake St. Croix TMDL Report, submitted by WDNR and MPCA to USEPA.	MPCA & WDNR (2012)
2011-2013	An interagency team began exploring lake stratification and internal loading as possible reasons for the observed decoupling between phosphorus inputs and chlorophyll <i>a</i> response.	Magdalene et al. (2013)
2013	Lake St. Croix TMDL Implementation Plan	Limnotech (2013)
2014	MCES calculated monthly and annual loads (1976-2013) for monitoring sites at Stillwater and Prescott; USGS conducted loading analyses (2012-14) on the Willow and Kinnickinnic Rivers.	MCES (2018)
2013-2015	Recently installed USGS flow gages at Stillwater and Prescott were used to estimate a historical flow record (1910-2010).	Ziegeweid and Magdalene (2015)
2014-2018	Two-dimensional hydrodynamic CE-Qual-W2 model of nutrient routing through Lake St. Croix.	Smith et al. (2018)

WATER QUALITY DRIVERS IN LAKE ST. CROIX

During this study, it was determined there are several hydrologic and ecological factors that drive the observed patterns in Lake St. Croix water quality. The following sections describe: 1) key hydrologic and ecological drivers, and 2) resulting water quality observations. All data described in this section are derived from the previous publications listed in Table 2.

Driver I: Elongated Water Body

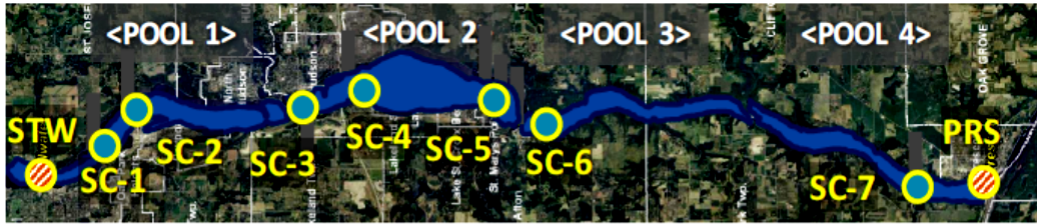
As described above, Lake St. Croix is an elongated body of water through which the river constantly flows: 25 miles long and 1.5 miles across at its widest point. The single largest input to Lake St. Croix is the river itself at Stillwater, which accounts for 94% of the lake outflow (Ziegeweid and Magdalene, 2015). In addition, the hydrologic transition at Stillwater, from the channelized flow of a big river to the slack water of a widened riverine lake, causes suspended sediments to collect in shallow Pool 1. Each of the three primary tributaries adds another 0.5-3.5% of the total outflow, including additional sediments and nutrients, but not enough to overwhelm mainstem loads, such that sediment accumulation rates decline and pool depths increase from Pool 1 to Pool 4.

Observation: Longitudinal Pattern to Water Quality

MCES has two monitoring programs that have been monitoring Lake St. Croix for comparable variables since 2005: two River Monitoring Program sites at Stillwater and Prescott, and seven Citizen Volunteer Lake Monitoring Program sites, located across all four pools of Lake St. Croix. Figure 5 includes the variables that were incorporated into the TMDL goals: decadal mean (2005-2014) of the summer measurements of Secchi depth (SD) clarity, total phosphorus (TP) concentration, and viable chlorophyll *a* (VChla) concentrations. It should be noted that the large river sites do not measure Secchi depth; the nearest analogous variable is total suspended solids (TSS) concentration, as it is a lake surface measurement of organic and inorganic solid particles that block light. Nonetheless, there is a clear longitudinal pattern, from upstream to downstream, in the decadal mean of all three variables: the highest turbidity (lowest clarity), highest TP, and highest VChla occurred at the upstream end of Lake St. Croix in Pool 1. These conditions gradually improve downstream; indeed, decadal means of clarity and TP satisfy the lake's water quality standards before the river reaches its outlet at Prescott, though VChla does not (Figure 5).

Summary

The dominant inflow at Stillwater, combined with the elongated shape of Lake St. Croix, creates a longitudinal pattern between two endpoints in Lake St. Croix: 1) turbid river-like conditions at Stillwater, and 2) clear lake-like conditions at Prescott. At Stillwater, there is low clarity, high phosphorus, and high algae concentrations. At Prescott, there is high clarity, low phosphorus, and low algae concentrations. The transition within Lake St. Croix, between river-like conditions and lake-like conditions, typically occurs in the middle of Pool 2.



Metropolitan Council Environmental Services (MCES) monitoring programs:

-  Large River Monitoring at two locations (Stillwater and Prescott)
-  Volunteer Lake Monitoring at seven locations (in all four pools)

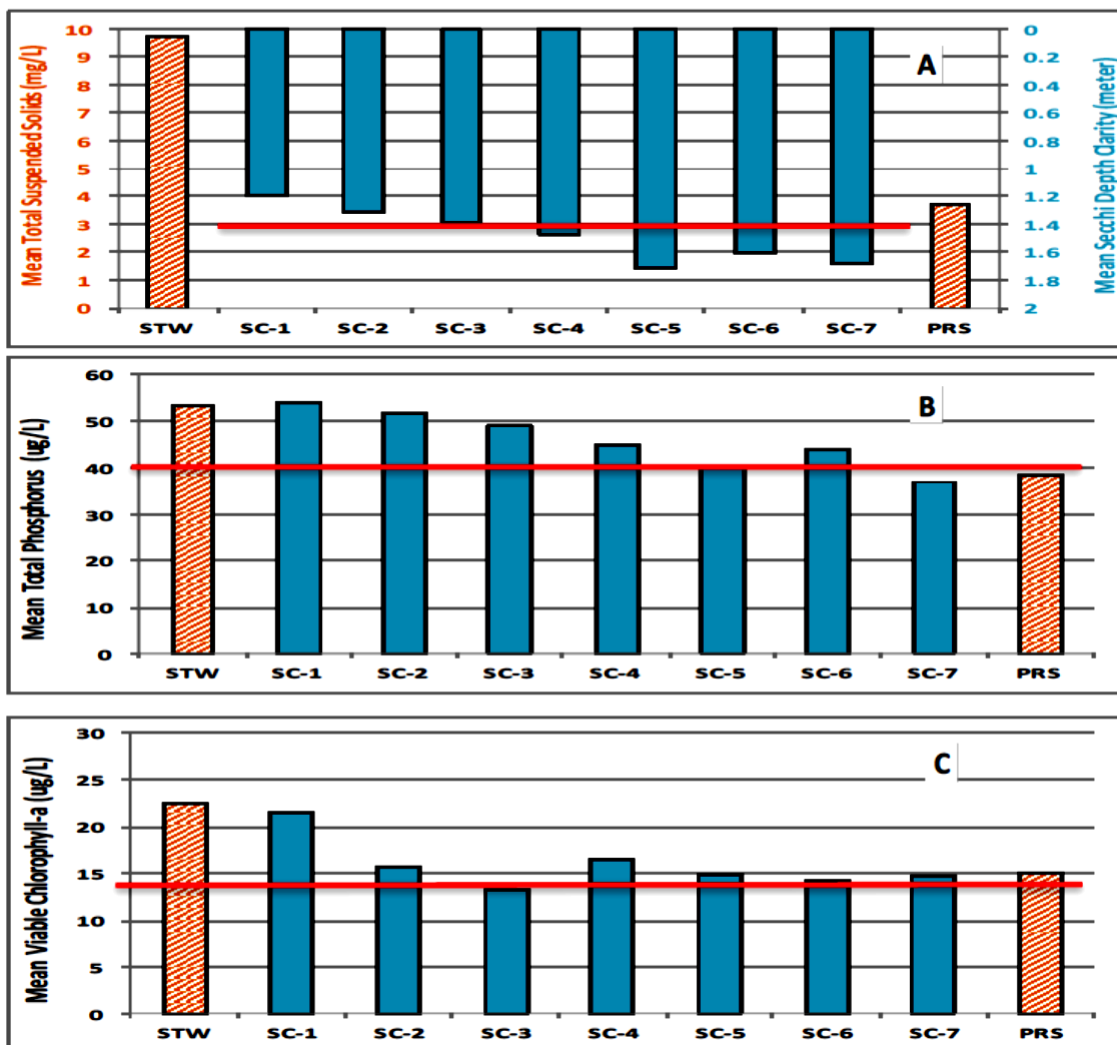


Figure 5. Decadal mean (2005-2014) of summer means (June-September) of (A) total suspended solids (TSS) concentration (mg/L) at two river sites and Secchi depth clarity in meters (m) at seven lake sites, (B) total phosphorus concentration (µg/L), and (C) viable chlorophyll a concentration (µg/L), compared with water quality standards incorporated into the TMDL goal (red lines).

Driver II: Seasonality of Temperature and Hydrology

Seasonality, driven by annual cycles in Midwestern temperature and water balance, has a strong overriding influence on the water quality patterns in Lake St. Croix. During the cold winters, the landscape is largely frozen and river flows reach an annual minimum (Figure 6). As temperatures warm in March, melting snow leads to increasing runoff. With peak snowmelt runoff in April, river discharges reach an annual maximum.

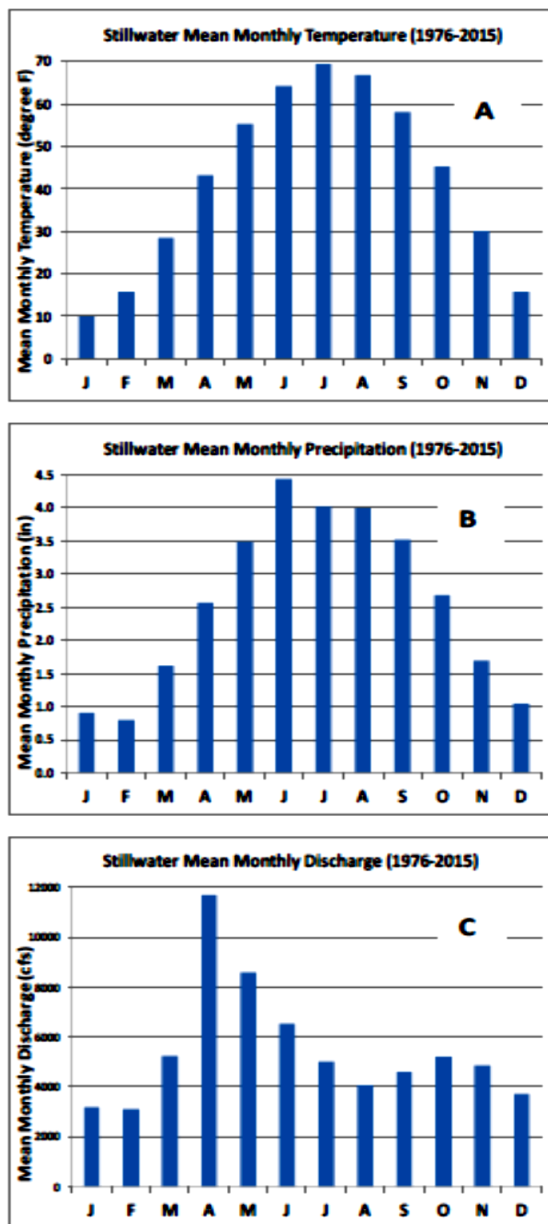


Figure 6. Monthly mean values of (A) temperature (Fahrenheit), (B) precipitation (inches), and (C) river discharge (cubic feet per second) at Stillwater, MN (1976-2015).

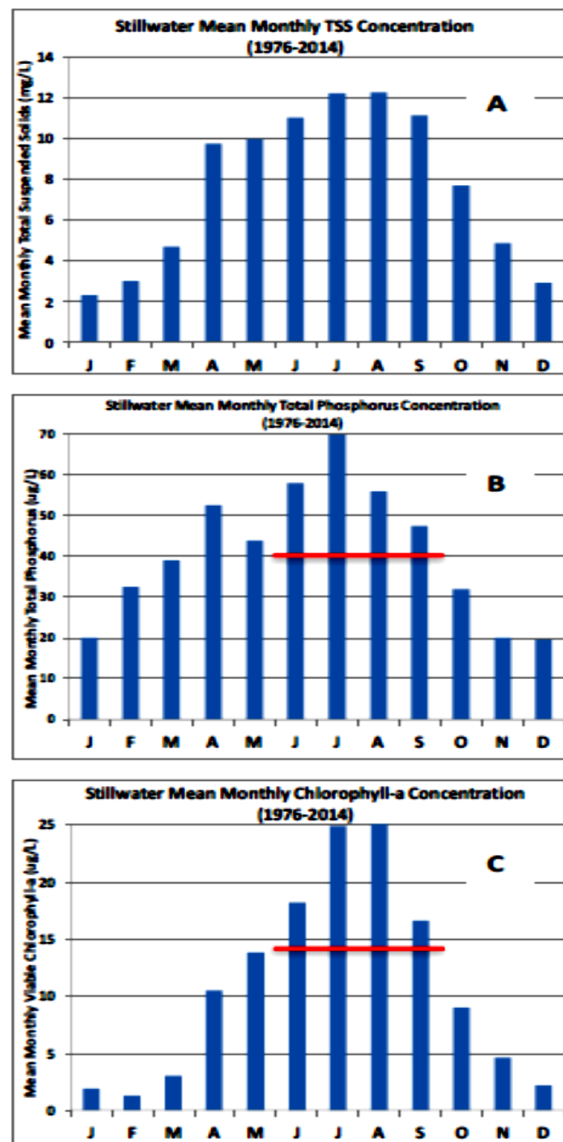


Figure 7. Monthly mean (A) total suspended solids (milligrams per liter), (B) total phosphorus (micrograms per liter), and (C) viable chlorophyll a concentrations (micrograms per liter) for the St. Croix River site at Stillwater, MN (1976-2014), compared with TMDL water quality standards (red lines).

Warming temperatures and spring leaf-out increase evapotranspiration of vegetation across the watershed, reducing average runoff despite summer storm events, such that river flows gradually decline over the summer. After crops are harvested in September and the first frost ends the growing season, river discharges are restored to a secondary maximum because of autumn rainfall. As winter approaches and air temperatures cool further, runoff ceases, and river flows decline through the remainder of the year.

Observation: Seasonal Pattern to Water Quality

Figure 7 shows the monthly mean concentrations of TSS, TP, and VChla at the MCES Stillwater site for 1976-2014. These variables are typically at an annual minimum in January and February, at the same time as annual minimum flow. With rapid snowmelt runoff in April, flows carry high sediment loads, and phosphorus concentrations exceed the 40 µg/L goal.

Algae begins growing with the influx of nutrients, but chlorophyll *a* concentrations stay below the 14 µg/L goal through the month of May. Even though river flows begin to decline into the growing season (Figure 6), runoff concentrations of suspended solids, phosphorus and chlorophyll *a* continue to climb, peaking in July and August, and remain above TMDL goals into September. The first frost ends the growing season and algae begins its seasonal decline. As flows decline late in the year, so do concentrations of TSS and TP.

Summary

The upper Midwestern extremes, of cold winters and hot summers, translate into annual cycles of water quality within Lake St. Croix. The low flows of winter carry few sediments and nutrients, and few species of algae grow at this time. Warming temperatures in April release a winter worth of snowmelt, carrying high sediment and nutrient loads, exceeding water quality standards and enabling the growth of springtime algae. In July and August, during the hottest part of the year and when river flow is at its lowest level of the growing season, algae growth and chlorophyll *a* concentrations reach their maximum for the year, often generating toxic blooms at this time. October and November rain storms bring in the last flush of sediments and nutrients prior to the winter slowdown.

Driver III: Lake Stratification

Lake St. Croix is more than a wide river; glacial-era scouring created an over- deepened channel that cut into bedrock. So, like many other lakes in the Upper Midwest, the pools of Lake St. Croix are deep enough that they thermally stratify each summer into a cold lake bottom (hypolimnion) and a warm lake surface (epilimnion). The unique difference about Lake St. Croix is that, as a riverine lake, the warm surface layer continuously flows over the four cold pools that are isolated from each other (Figure 8). Because warm water does not sink, thermal stratification cuts off cold bottom waters from replenishment by atmospheric oxygen, and cold bottom waters become progressively less oxygenated (hypoxic). In addition, dead algae and other settling organic matter consume the remaining oxygen as they decay. When the lake bed becomes anoxic (lacking all oxygen), phosphorus starts to be released from the bed sediments. This process, called internal loading, releases phosphorus into the hypolimnion during thermal stratification.

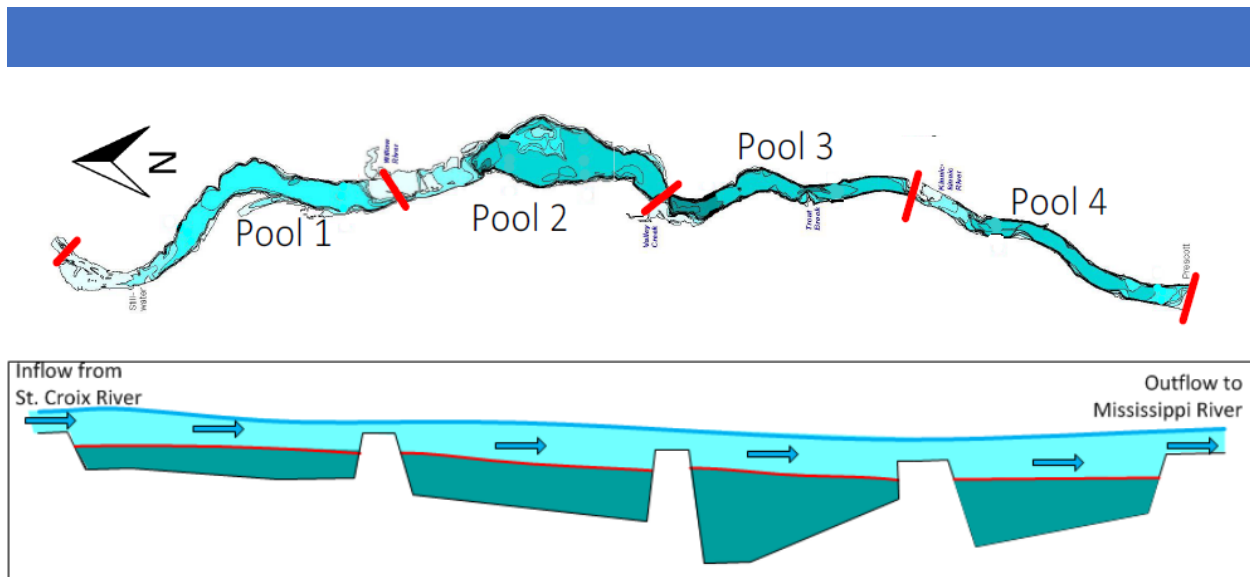


Figure 8. Map view (top figure) and longitudinal cross-section (bottom figure) of Lake St. Croix, showing the warm, oxygen-rich epilimnion sliding over the cold, oxygen-depleted hypolimnion. Red lines in the top figure represent boundaries of the four pools. Red lines in the bottom figure represent the thermoclines of each pool, and arrows represent the direction of flow.

Observation: Anoxia and Phosphorus Release in Lake Bottom

As an extension of their activities for the MCES Citizen Volunteer Lake Monitoring program, in 2008 Harper Consulting, Inc. began measuring depth profiles of temperature, pH, specific conductivity, and dissolved oxygen at all seven lake monitoring sites during summer months (Johnson 2017). They have determined that the pools begin to stratify in June and are often fully stratified by July (Figure 9). Stratification persists into September, when the epilimnion cools to the temperature of the underlying hypolimnion, at which time the lake water turns over and becomes thoroughly mixed. When this happens, the anoxic (<0.5 mg/L DO) phosphorus- rich waters become mixed with the overlying river, causing the entire river to become nearly hypoxic (5-6 mg/L DO) for a brief period (Figure 9).

Lake stratification profiles vary with flow condition (Figure 10). High flows oxygenate more water at the surface, creating a deeper epilimnion. However, higher flows decrease algae abundance and respiration, so even though the epilimnion is deeper, DO concentrations are lower in the epilimnion in high-flow years compared to low-flow years.

Summary

By the heat of July, Lake St. Croix has stratified. The warm surface layer prevents the cold bottom layer from accessing atmospheric oxygen, and excess TP is released into the cold bottom layer. As temperatures start cooling in September, the phosphorus-rich bottom waters become fully mixed with the lake surface.

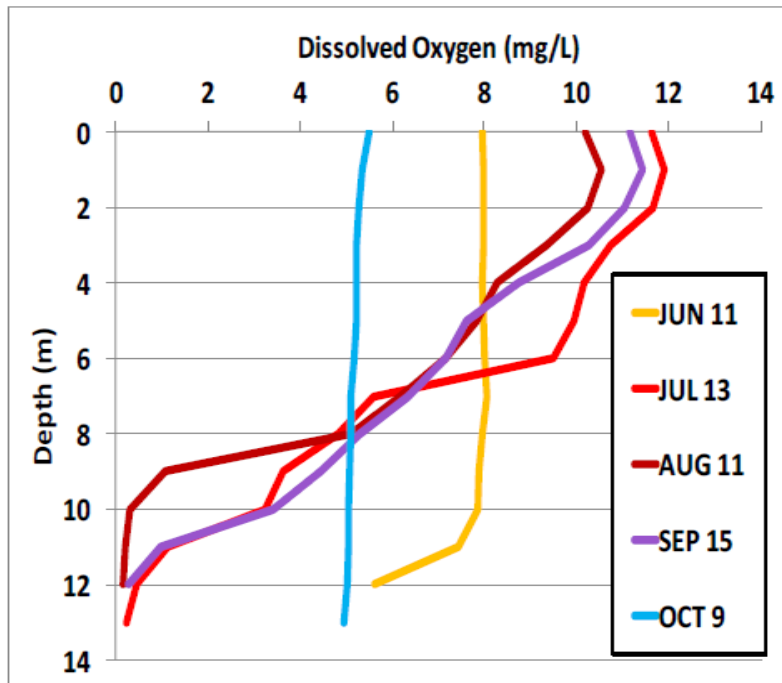


Figure 9. Dissolved oxygen (milligrams per liter) profiles with depth (meters) at MCES lake monitoring site SC-7, in Pool 4 near the outlet at Prescott, for five measurement dates in 2009.

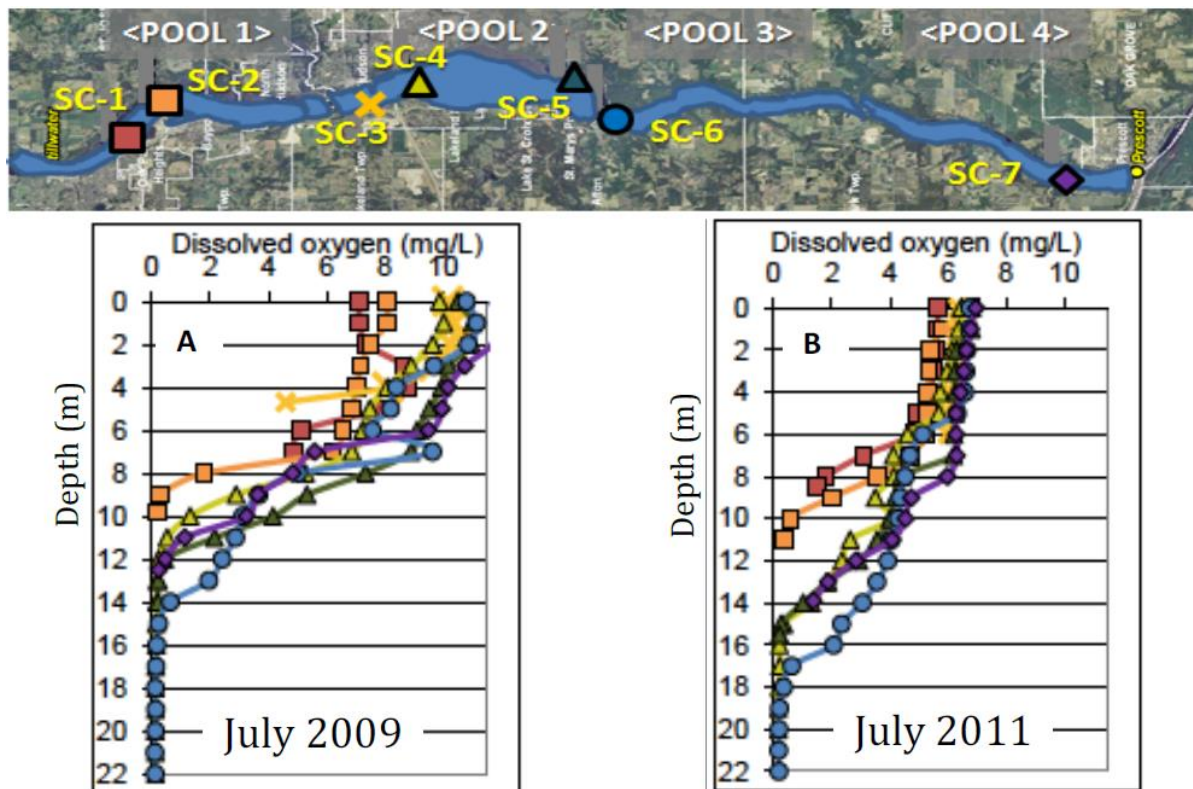


Figure 10. Dissolved oxygen (milligrams per liter) profiles with depth (meters), at MCES lake monitoring sites during (A) low-flow conditions of July 2009 and (B) high-flow conditions of July 2011.

Driver IV: High Flows and Low Flows Alternate in Nearly Decadal Cycles

The USGS has been measuring discharge in the St. Croix River since the late 1800s and has maintained a record of daily mean flows at St. Croix Falls, WI since 1910. More recently, USGS flow gages were installed on the St. Croix River at Prescott in 2007 and at Stillwater in 2011. Ziegeweid and Magdalene (2015) compared the measured discharge at these two sites against the historical record at St. Croix Falls, and derived regression equations that greatly improved estimated historical inflows and outflows for Lake St. Croix. Based on percent of variability explained by the regressions, the estimation of historical inflows at Stillwater improved by 8% compared to previous estimation methods (from 90% to 98%), and the estimation of historical outflows at Prescott improved by 17% (from 77% to 94%). Subsequently, these new estimated flow records were analyzed using the statistical technique of moving window averages of the daily mean flows. A variety of averaging periods (i.e., window sizes) were assessed, from 30-year means to 1.5-year means. The difference between the five-year mean and the ten-year mean was found to yield an overall pattern across the century (Figure 11): about 4-5 years of high-flow conditions alternating with about 4-5 years of low-flow conditions, with the cycle repeating every 9 years, on average. Note that there is plenty of variability across both flow conditions, but the difference in the means fell in a regular pattern.

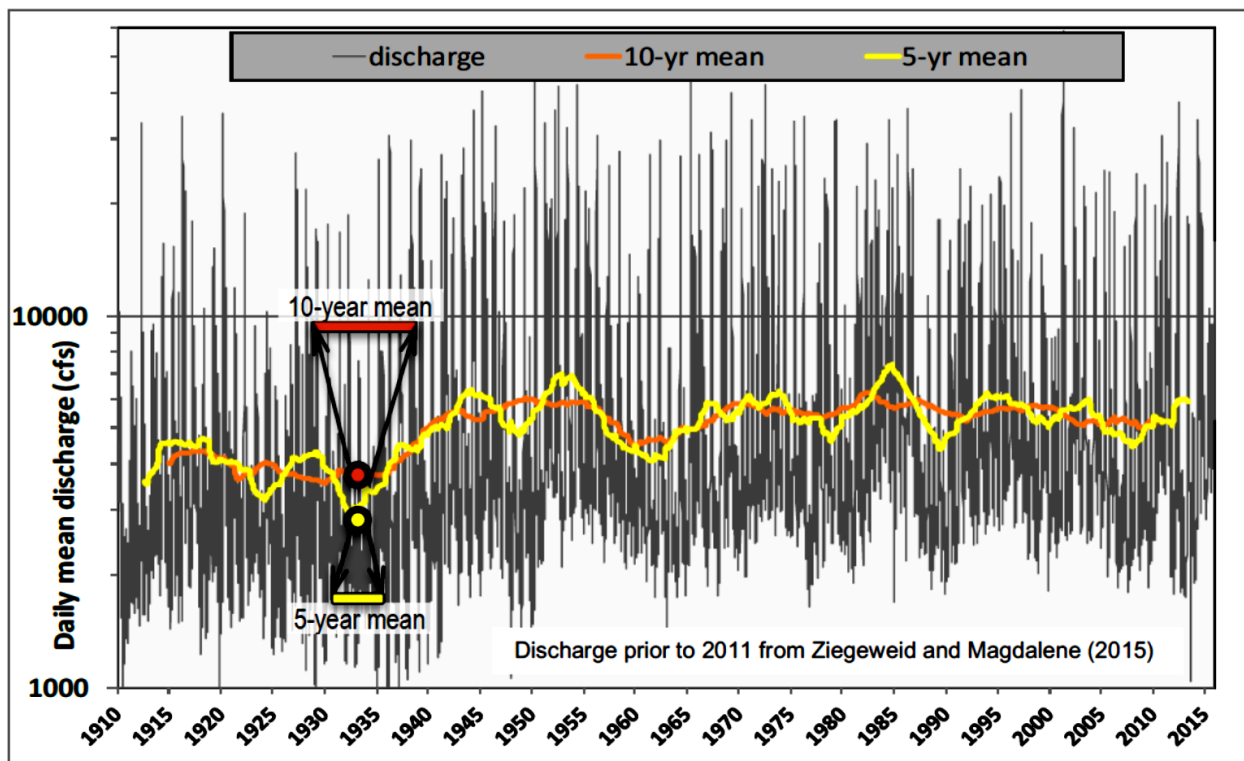


Figure 11. Historical daily discharge (1910-2015) on the St. Croix River at Stillwater, overlain by 5-year (yellow) and 10-year (orange) moving averages. Note that averages are calculated and applied to the centroid of the averaging window, such that each date has a daily mean, a 5-year mean, and a 10-year mean, except on both ends of the historical record.

River discharge is often driven by precipitation, so the cycles in discharge were evaluated against precipitation. The same moving average analysis, 5-year mean minus 10-year mean, was applied to the Stillwater monthly precipitation and the monthly discharge records (1910-2015) and compared in Figure 12. Statistical correlation is indicated by Pearson's coefficient = 0.79. The relationship can be summarized: negative values of the difference in means represents drier conditions contributing to a low-flow regime, while positive values of the difference in means represent wetter conditions contributing to a high-flow regime. Thus, in preparation for analysis of water quality data, the 1976-2015 monitoring history was delineated into low-flow and high-flow periods, using the moving average technique (Figure 13). The mean (4,707 cfs) and range (1,930 to 6,340 cfs) of flow during low-flow periods were statistically different ($\alpha = 0.05$) than the mean (6,297 cfs) and range (1,740 to 7,970 cfs) of flow during the high-flow periods, which raised a couple questions: (1) How do these nearly decadal cycles in flow condition influence water quality? (2) Are there also previously unidentified alternating cycles in water quality that could inform our understanding of Lake St. Croix ecology?

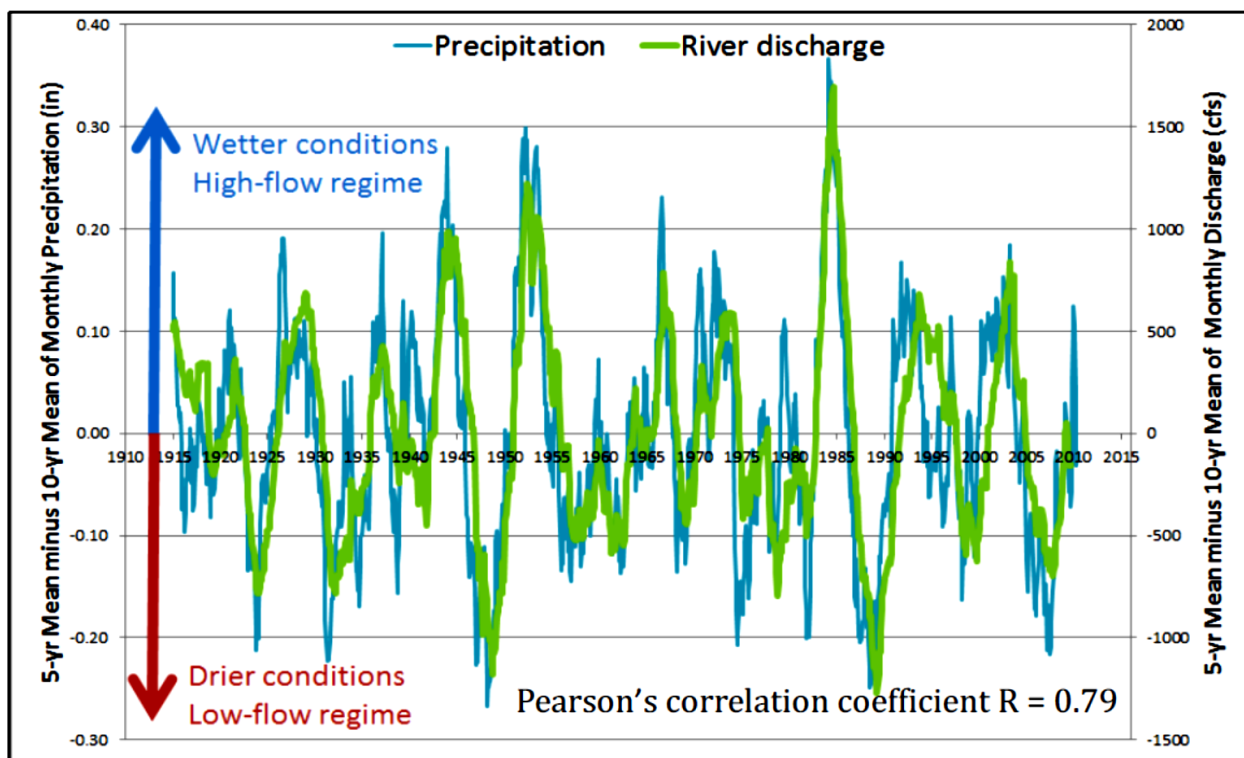


Figure 12. Comparison of moving window analysis (5-year mean minus 10-year mean) results for monthly precipitation (inches) and monthly discharge (cubic feet per second) at Stillwater, Minnesota.

Observation: Water Quality Varies with Decadal Flow Condition

The nine MCES monitoring sites were assessed for the decade 2005-2014. According to the moving-average analysis, 2005-2009 was defined as low-flow condition and 2010-2014 was defined as high-flow condition.

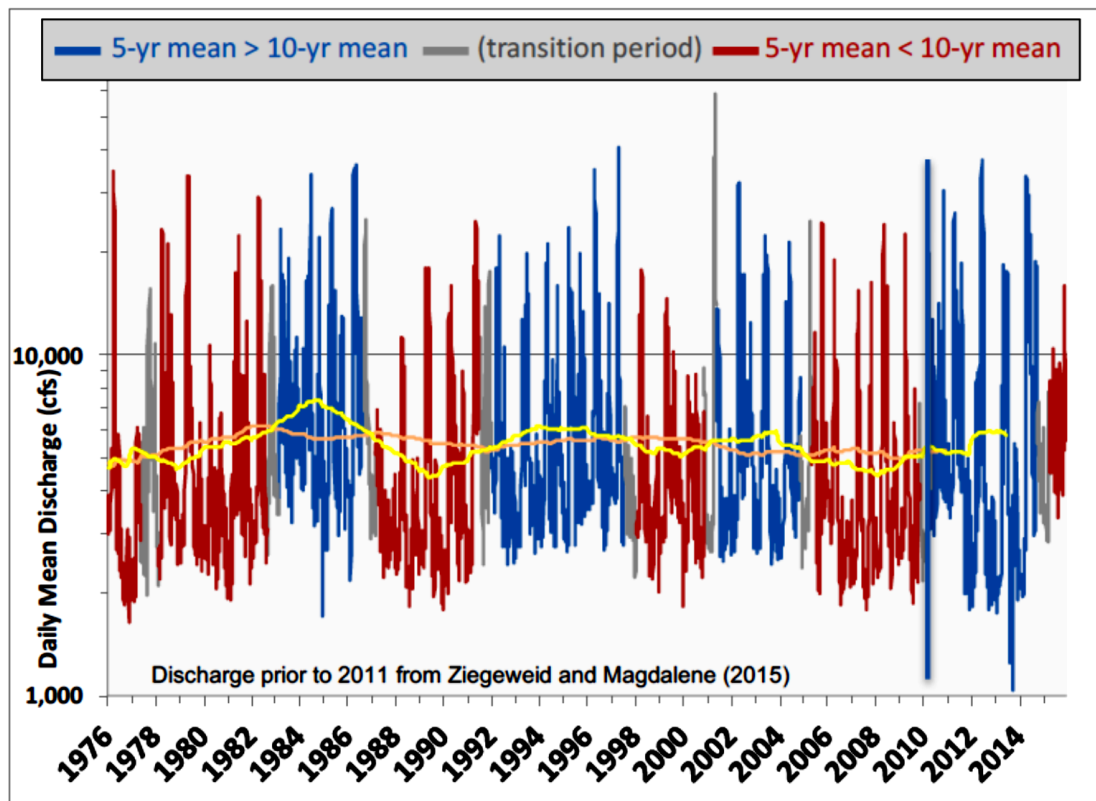


Figure 13. Forty years of St. Croix River daily discharge (cubic feet per second) at Stillwater, Minnesota (1976-2015), showing delineation of drier, low-flow periods (in red) and wetter, high-flow periods (in blue) based on moving window analysis. These periods were used to separate water quality data into two groups representing high-flow conditions and low-flow conditions. The 5-year (yellow) and 10-year (orange) moving averages introduced in Figure 11 are also included in the graph.

Comparison of the water quality data collected during low-flow and high-flow conditions revealed distinct differences in water quality. The measurements of clarity, total phosphorus, and chlorophyll *a* during low-flow periods were statistically different ($\alpha = 0.05$) than those measurements during high-flow periods.

Figure 14 compares the low-flow, average-flow, and high-flow summer mean (June-September) TSS concentrations at the two river sites and summer mean (June-September) Secchi depth clarity at the seven lake sites. During high-flow conditions, TSS is higher and clarity is lower compared to low-flow conditions. During the low-flow conditions of 2005-2009, all lake sites met the TMDL clarity standard, whereas during the high-flow conditions of 2010-2014, the first three lake sites above Pool 2 did not meet the clarity standard.

Figure 15 compares the low-flow, average-flow, and high-flow summer mean (June-September) TP concentrations at the two river sites and the seven lake sites. During high-flow conditions, TP is higher at all sites than during low-flow conditions. During the low-flow conditions of 2005-2009, all lake sites except those within Pool 1 met the TMDL phosphorus standard, whereas during the high-flow conditions of 2010-2014, none of the lake sites met the phosphorus standard.

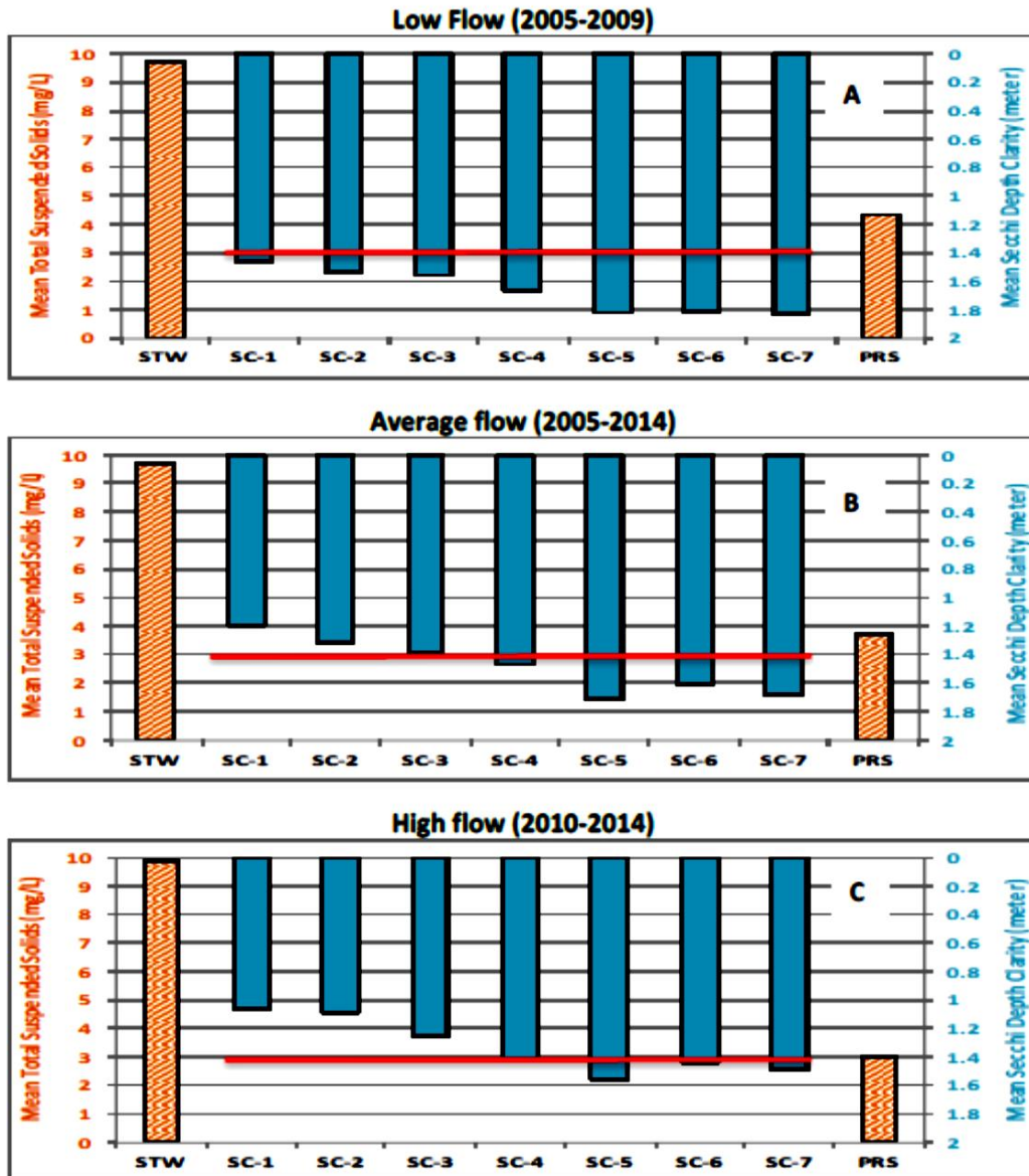
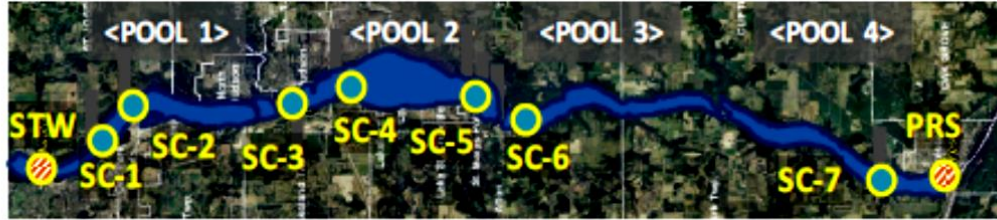


Figure 14. Comparison of summer mean (June-September) total suspended solids concentrations (milligrams per liter) at two river sites and summer mean secchi depth clarities at seven lake sites during (A) low-flow, (B) average-flow, and (C) high-flow conditions, 2005-2014, compared with the TMDL water quality standard (red lines).

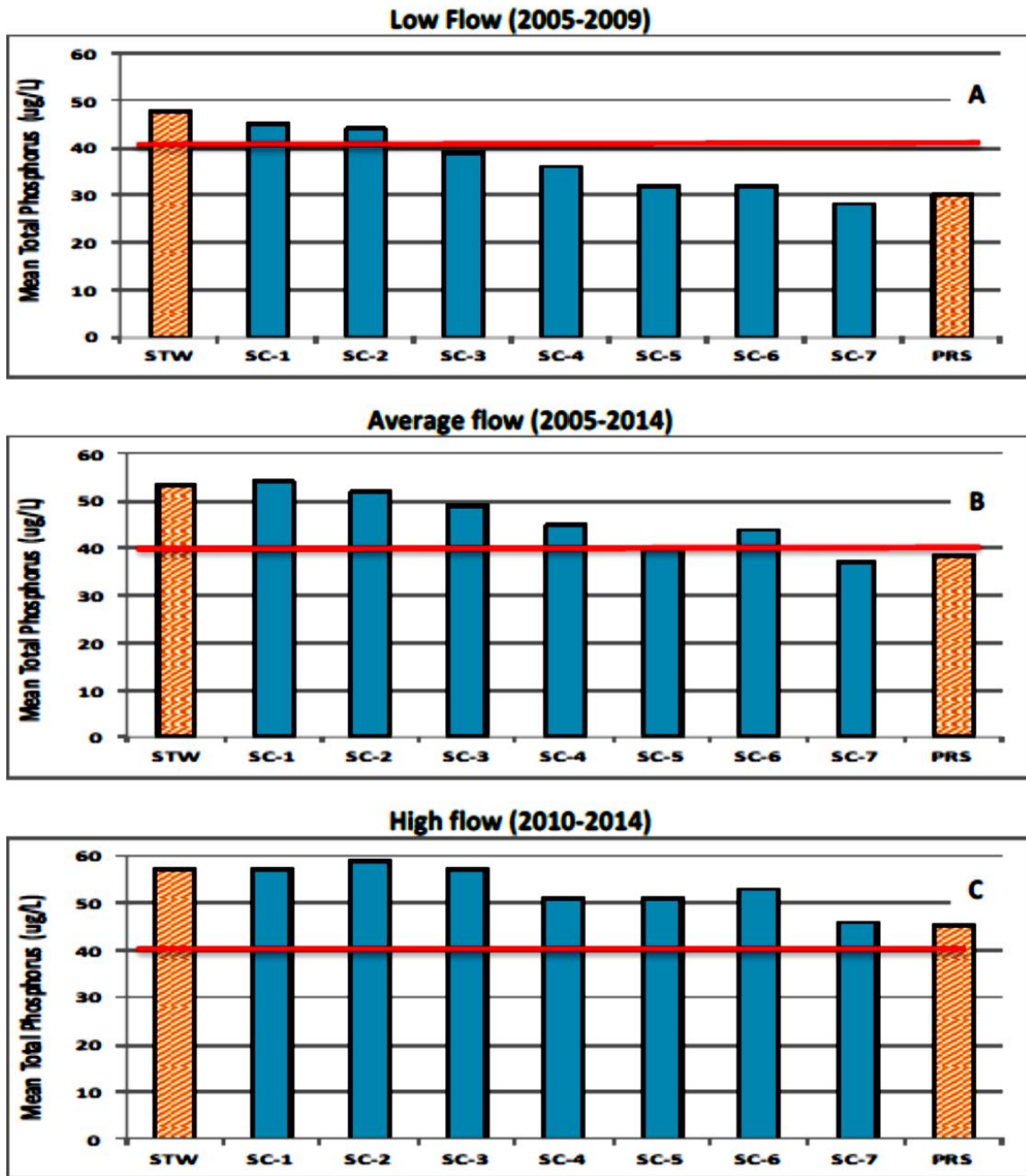
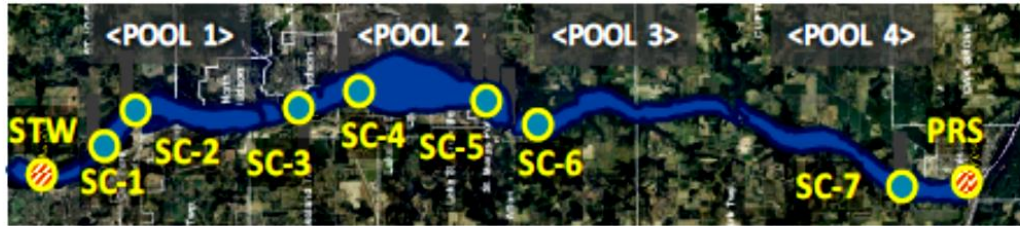


Figure 15. Comparison of summer mean (Jun-Sep) total phosphorus concentrations (micrograms per liter) at two river sites and seven lake sites during (A) low-flow, (B) average-flow, and (C) high-flow conditions, 2005-2014, compared with the TMDL water quality standard (red lines).



Figure 16 compares the low-flow, average-flow, and high-flow summer mean (June-September) VChla concentrations at the two river sites and the seven lake sites. During low-flow conditions VChla is higher at all sites than during high-flow conditions. Slower flows allow more time for algae to grow and reproduce, whereas faster flows sweep algae away, inhibiting reproduction. During the low-flow conditions of 2005-2009, none of the lake sites met the TMDL chlorophyll standard, whereas during the high-flow conditions of 2010-2014, most of the lake sites below Pool 1 met the chlorophyll standard.

Summary

During low-flow periods, the monitoring sites of Lake St. Croix showed increased clarity, decreased phosphorus, and increased chlorophyll *a*, compared to decreased clarity, increased phosphorus, and decreased chlorophyll *a* during high-flow periods. Lake water clarity and phosphorus concentrations improved during the relative calmness of low-flow conditions, but those same conditions allow for abundant algal growth. On the other hand, high-flow conditions deliver muddy waters that carry phosphorus to the lake but reduce clarity to the extent that inhibits light penetration and growth of algae.

COMBINED EFFECTS OF DRIVERS

To assess the combined influence of longitudinal lake shape, seasonality, lake stratification, and alternating flow regimes on Lake St. Croix water quality, the 1999-2015 lake monitoring data set was not large enough to provide a statistically significant amount of data in each of the above subdivisions for analysis. Therefore, the 1976-2014 record of MCES river monitoring at Stillwater and Prescott was analyzed by month and flow condition (defined by the difference in moving averages). However, the water quality variables were measured less frequently than discharge, creating smaller groups of data that were sensitive to extreme values. Therefore, median monthly values were analyzed for the water quality variables.

This analysis directly addresses three of the four drivers, enabling a discussion of the combined influences of longitudinal, seasonal, and flow-related patterns in water quality. And although the surface-sampling method at the two large river monitoring sites does not directly measure lake stratification at the two endpoints of the lake, the influence of lake stratification does occur in the monitoring record and will be discussed below.

Note that the figures and table in this section use the same color designations as those in Figure 13: drier, low-flow conditions are represented in red; and wetter, high-flow conditions are represented in blue.

River Discharge

The recent analysis of St. Croix River historical discharge records at Stillwater and Prescott (Ziegeweid and Magdalene 2015) enabled a detailed assessment of river discharge at these locations that existed prior to installation of the USGS gages (in 2011 and 2007, respectively). Figure 17 shows the monthly mean discharge at Stillwater and Prescott for both low-flow and

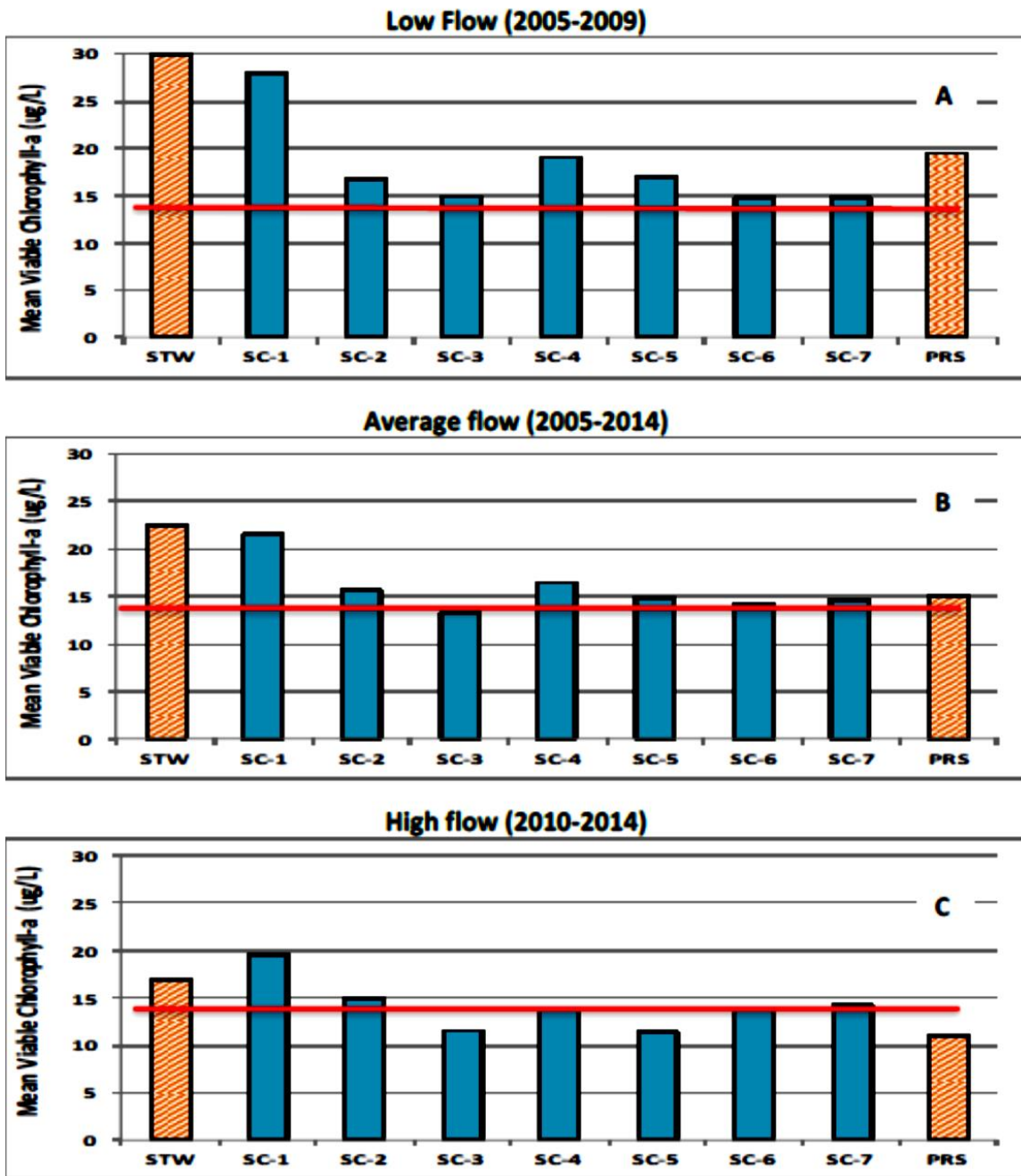
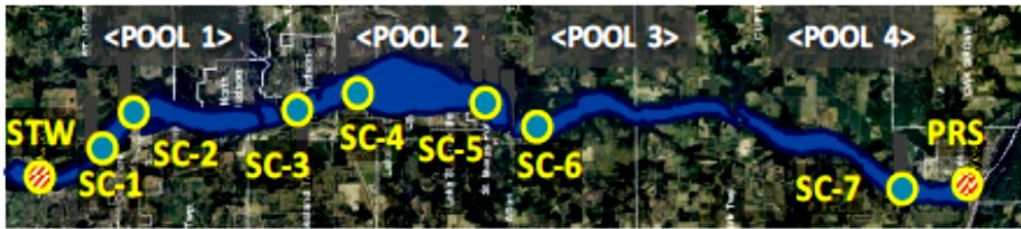


Figure 16. Comparison of summer mean (Jun-Sep) viable chlorophyll a concentrations (micrograms per liter) at two river sites and seven lake sites during (A) low-flow, (B) average-flow, and (C) high-flow conditions, 2005-2014, compared with the TMDL water quality standard (red lines).

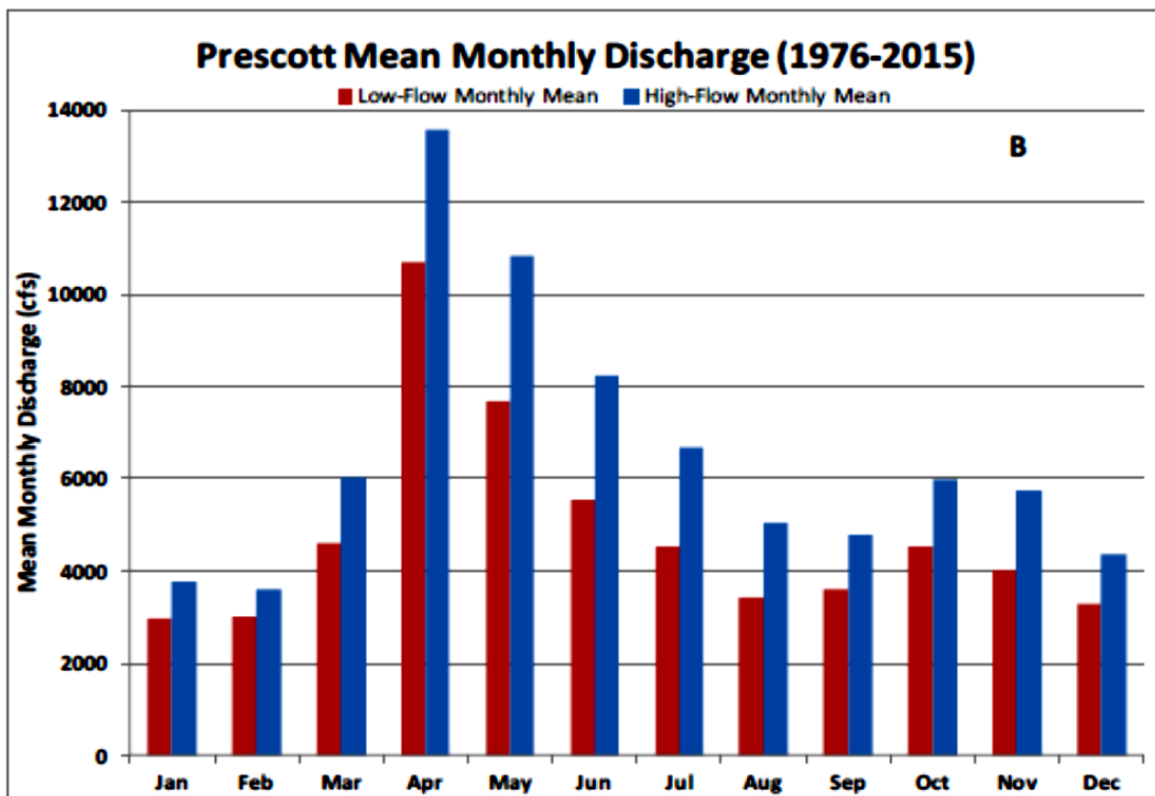
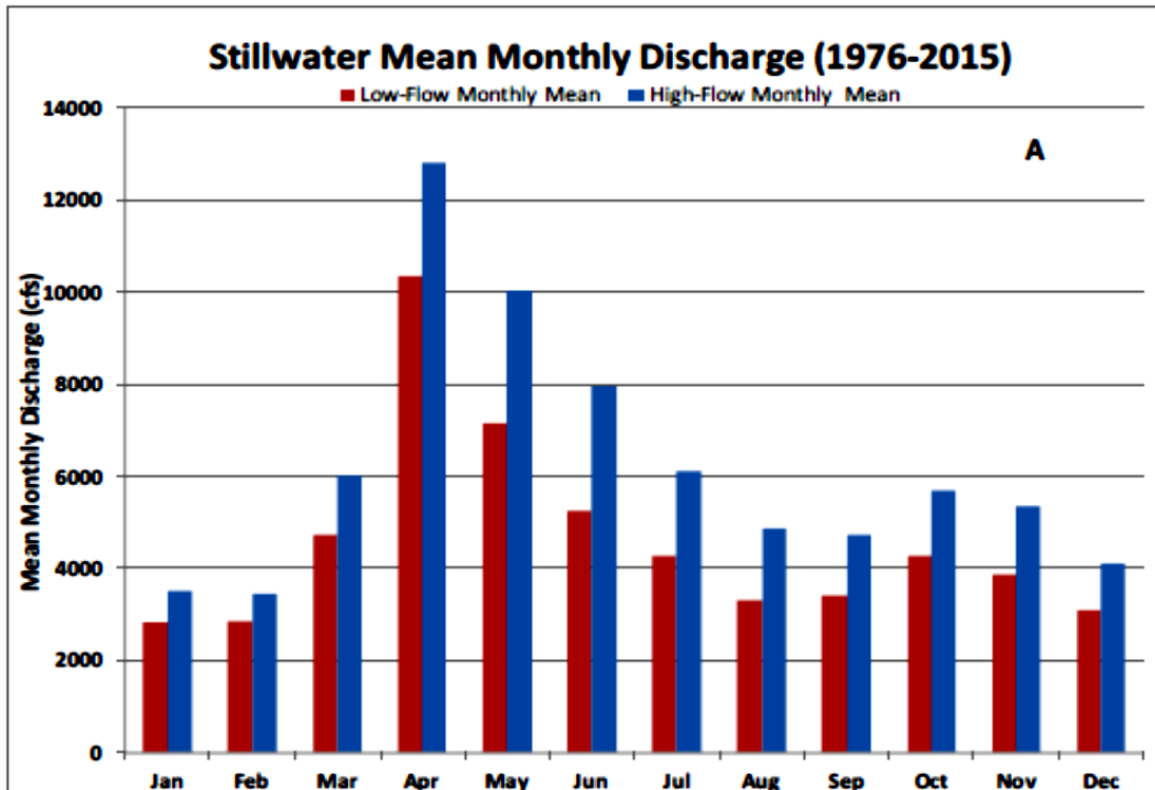


Figure 17. Comparison of monthly mean river discharges (cubic feet per second) during low-flow and high-flow conditions at (A) Stillwater, MN and (B) Prescott, WI, 1976-2015.

high-flow conditions during 1976-2015. The average long-term gain in discharge between Stillwater and Prescott of 300 cfs is mostly the result of the Wisconsin tributaries; that gain is clearly not distributed evenly across the months of the year. The smallest gains occur during winter, whereas the largest gains occur during April snowmelt and early summer storm runoff.

Both sites match the seasonal pattern of the long-term monthly mean discharges in Figure 6; the difference between the sites in seasonal discharge pattern is minimal. However, when we assess the seasonal patterns in water quality, we see interesting differences between the two endpoints of the lake.

Clarity

The MCES River Monitoring Program does not measure one of the TMDL criteria, Secchi depth clarity. The nearest analogous variable is total suspended solids (TSS) concentration, which is a lake-surface measurement of organic and inorganic solid particles that block light. Figure 18 shows monthly median TSS concentrations at Stillwater and Prescott for both low-flow and high-flow conditions during 1976-2014. There is a large difference in TSS between the two endpoints of the lake. Relatively high concentrations of TSS flow from the St. Croix basin into Lake St. Croix at Stillwater, while very little of that TSS flows out of Lake St. Croix into the Mississippi River at Prescott. The St. Croix River is flowing system, but the great depth of Lake St. Croix enables capture of most sediments and organic particles, serving as a sediment trap.

Under low-flow conditions at Stillwater, monthly TSS concentrations peak in the spring and stay high all summer, probably because of excess algal growth during low flows. Under high-flow conditions at Stillwater, TSS does not peak until August during seasonally low flows. In contrast, at Prescott, monthly median TSS concentrations are always higher under low-flow conditions than under high-flow conditions. Since the lake serves as an efficient sediment trap, the TSS measurements at Prescott might be dominated by suspended organic particles like algae, which is most abundant in low-flow conditions.

Phosphorus

With regard to the nutrient phosphorus, there are informative differences between the two endpoints of the lake. Figure 18 shows monthly median TP concentrations at Stillwater and Prescott for both low-flow and high-flow conditions during 1976-2014, compared with the TMDL water quality standard of 40 µg/L (June-September mean). Generally, TP concentrations are higher at Stillwater than at Prescott. The measurement of total phosphorus includes particulate phosphorus, that is, phosphorus that attaches to sediment particles. Thus, there is some similarity between the seasonal patterns in TSS (Figure 18) and TP (Figure 19) at each site.

In addition to particulate phosphorus, TP includes a component of dissolved phosphorus that is more chemically reactive within the lake. This component is active in cell production and plant growth but is passively carried down to the hypolimnion when dying organisms settle toward the lake bottom. During summertime lake stratification, storage of phosphorus continues to build up in the hypolimnion of all four pools, resulting in a large difference in TP concentrations between Stillwater and Prescott in midsummer (Figure 19). When the lake surface cools in autumn and

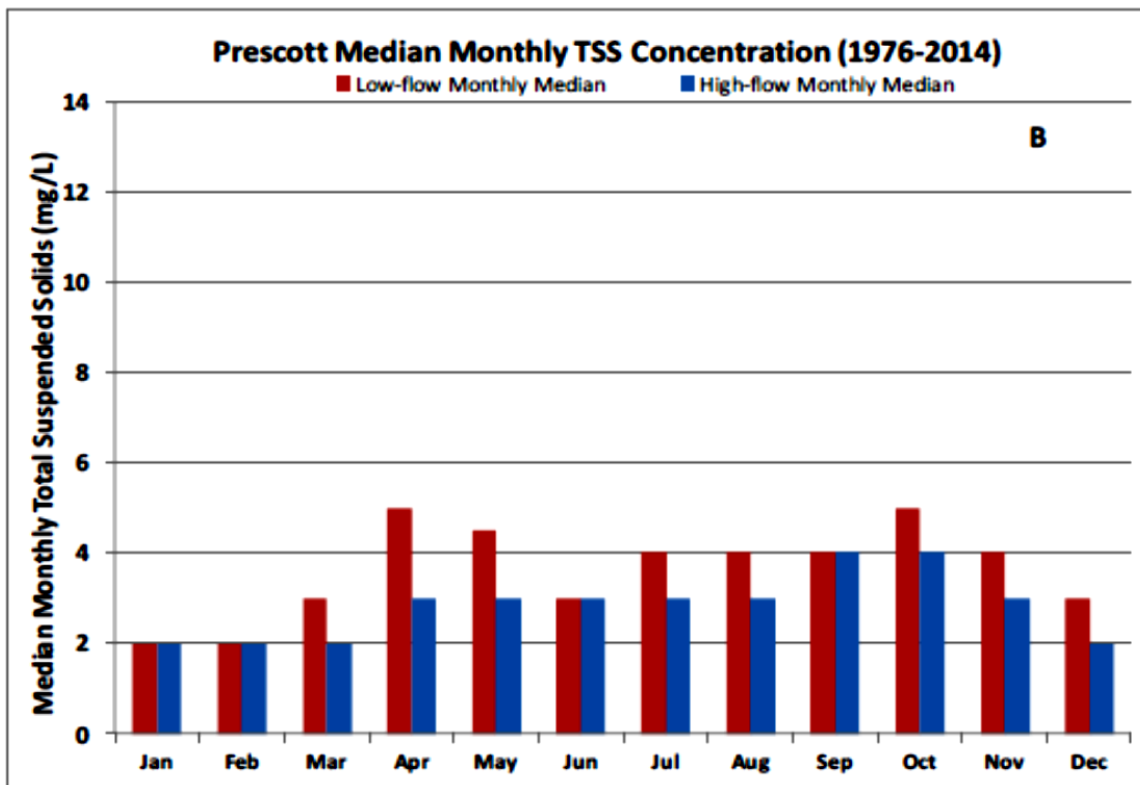
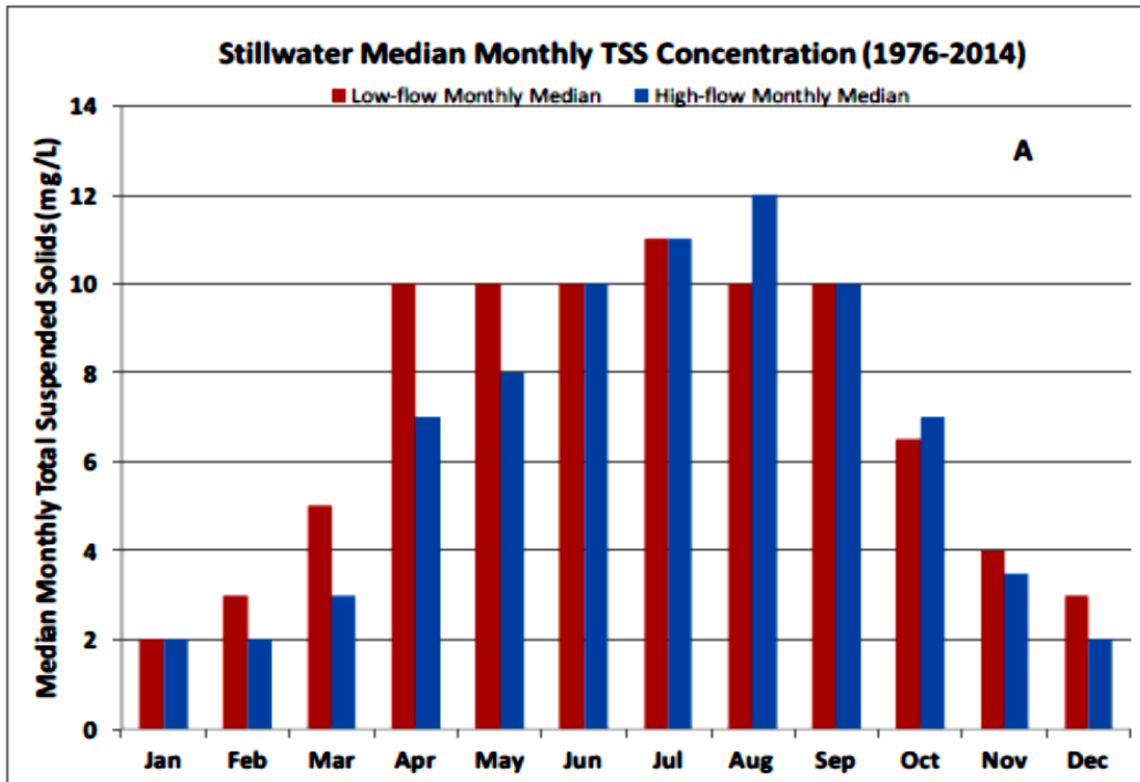


Figure 18. Comparison of monthly median total suspended solids concentrations (milligrams per liter) during low-flow and high-flow conditions at (A) Stillwater, MN and (B) Prescott, WI, 1976-2015.

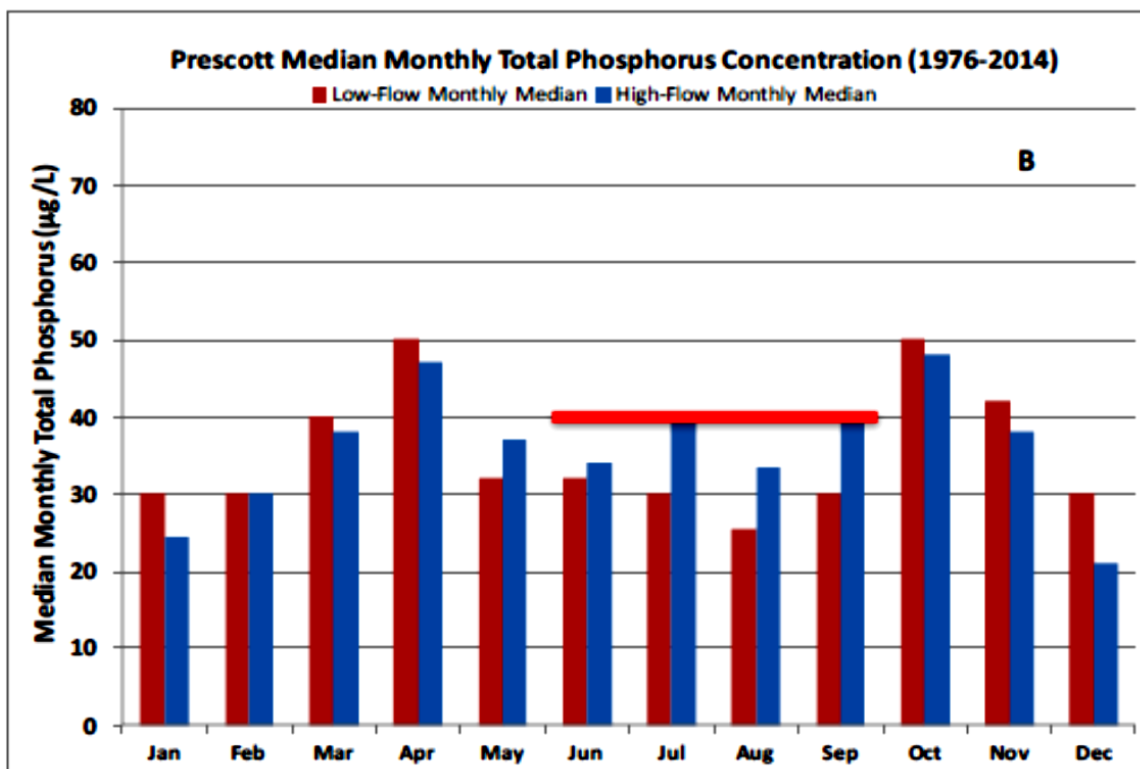
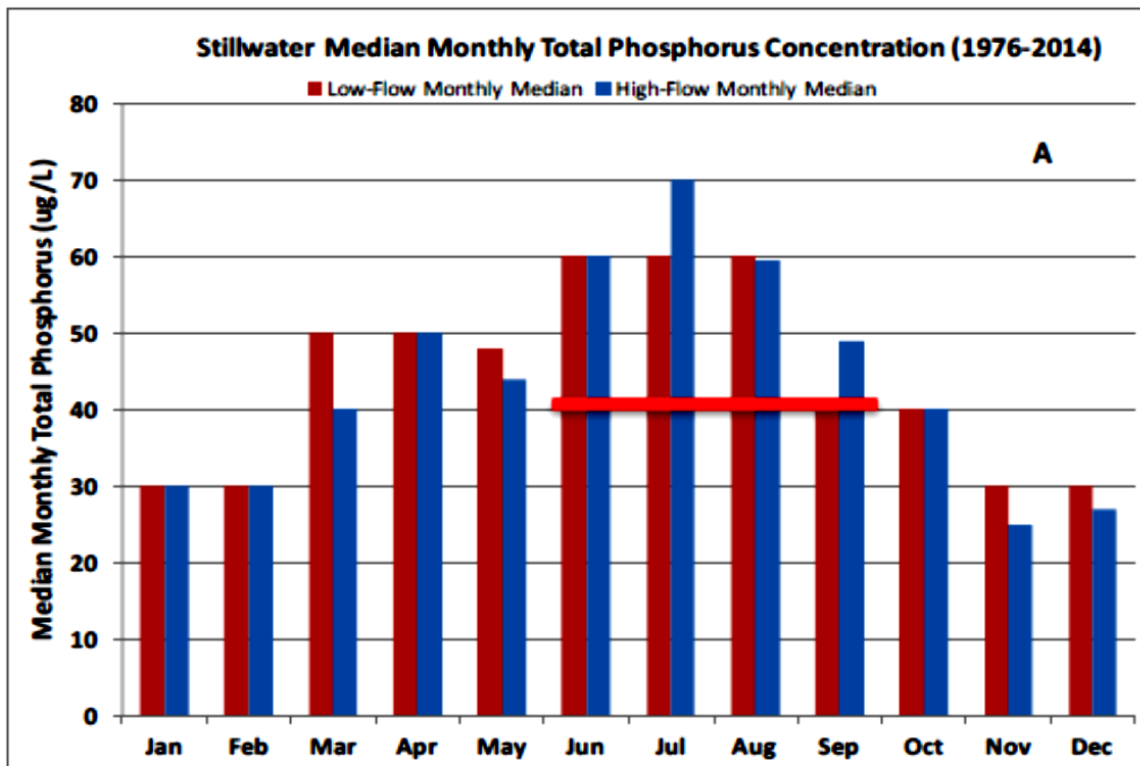


Figure 19. Comparison of monthly median total phosphorus concentrations (micrograms per liter) during low-flow and high-flow conditions at (A) Stillwater, Minnesota and (B) Prescott, Wisconsin, 1976-2015. Red line is summer mean (June-September) TMDL standard for Lake St. Croix.

the pools turnover, mixing the pools from top to bottom, this stored mass of phosphorus in the hypolimnion is washed downstream, spiking TP concentration at Prescott far above that delivered by basin runoff at Stillwater (Figure 19).

The TMDL water quality standard criteria are designed as whole-lake averages across the lake monitoring sites; however, comparing the two river sites against the TMDL criteria can be informative. Again, TP concentrations at Stillwater peak in summer, whereas concentrations at Prescott peak in spring and autumn. The difference in seasonal pattern between the two river sites indicates that the upstream end of the lake at Stillwater will likely exceed a summer average of 40 µg/L, under any flow condition. On the other hand, the long-term (1976-2014) monthly medians in the downstream end of the lake at Prescott are already achieving the TMDL standard for all flow conditions.

Chlorophyll *a*

Viable chlorophyll *a* (VChla) is a good indicator of active algal growth because it measures the chlorophyll *a* concentrations in only living (viable) plant cells. Plant cells that are dying or dead, but have not settled to the lake bottom, are not part of this measure. Figure 20 shows monthly median VChla concentrations at Stillwater and Prescott for both low-flow and high-flow conditions during 1976- 2014, compared with the TMDL water quality standard of 14 µg/L (June- September mean). As with the previous water quality variables, VChla is higher at Stillwater than at Prescott. However, VChla was more controlled by flow than the other variables; at both sites and during all months, low-flow concentrations were higher than high-flow concentrations (Figure 20). All plants need time to grow and reproduce. Therefore, floating, unrooted plants like algae are more productive in low-flow conditions.

Chlorophyll *a* is a generalized indicator of biological activity in that it measures all sources of chlorophyll *a*, no matter what plant species are present within a water sample. A previous report on Lake St. Croix (Magdalene et al. 2013) documented that different algal groups (e.g., diatoms, green, blue-green, brown) dominate in different months or seasons of the year based on variations in temperature and water quality that a specie can tolerate. A few species tolerate the icy winter and cold spring temperatures (e.g., the month of May in Figure 19B), but by midsummer the potentially toxin-producing blue-green algae group dominates the peak VChla concentrations of the season.

The TMDL water quality standard criteria are designed as whole-lake averages across the lake monitoring sites; however, comparing the two endpoints of Lake St. Croix at the MCES river sites against the TMDL criteria can be informative. The difference in seasonal pattern between the two river sites (Figure 20) indicates that the upstream end of the lake at Stillwater will likely exceed the summer average of 14 µg/L, especially under low-flow conditions. On the other hand, the long-term (1976-2014) monthly medians in the downstream end of the lake at Prescott are already achieving the TMDL standard for high-flow conditions, and perhaps for low-flow conditions.

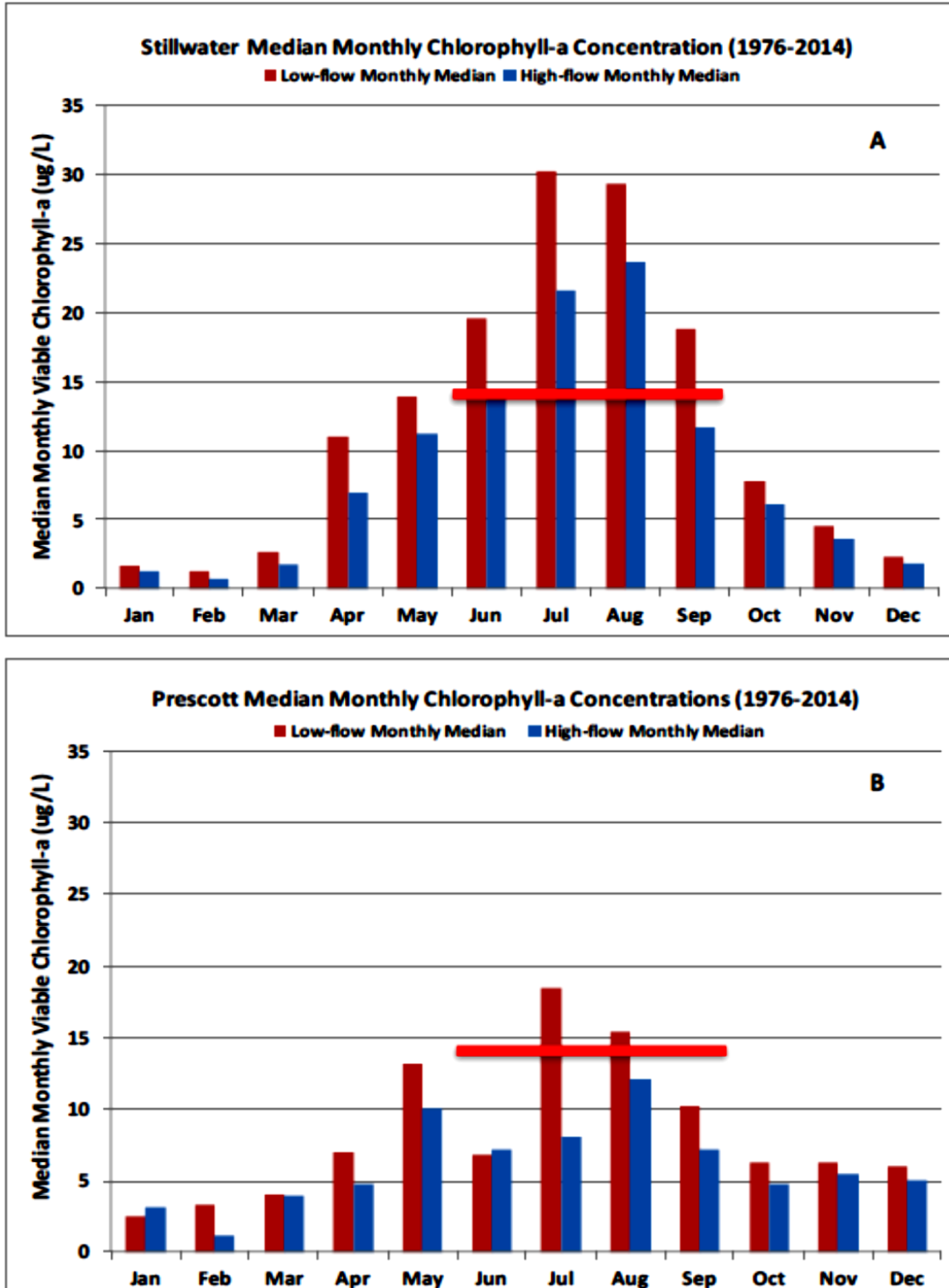


Figure 20. Comparison of monthly median viable chlorophyll a (VChla) concentrations (micrograms per liter) during low-flow and high-flow conditions at (A) Stillwater, MN and (B) Prescott, WI, 1976-2015. Red line is summer mean (June-September) TMDL standard for Lake St. Croix.

Summary

The seasonal differences between the two river sites are informative:

- TSS and TP peaked in summer at Stillwater but peaked in spring and autumn at Prescott.
- VChla was always higher during low-flow conditions than during high-flow conditions for any given month.
- Excess TP concentrations at Prescott in October and November most likely result from mixing after lake de-stratification.

To minimize the effect of extreme values while assessing the combined influence of water quality drivers in Lake St. Croix, monthly medians of water quality variables were used for Figures 18-20. However, the TMDL water quality standards are designed as a summer mean (June-September). Therefore, the summer mean of TSS, TP, and VChla for the two endpoints of Lake St. Croix, Stillwater and Prescott, are listed in Table 3 for 1976-2014 low-flow, period-of-record average, and high-flow conditions. The data in Table 3 support additional points of this section:

- The highest concentrations of TSS, TP, and VChla occur at Stillwater where basin runoff enters Lake St. Croix, and concentrations are much lower where Lake St. Croix flows into the Mississippi River at Prescott.
- The “turbid river” endpoint at Stillwater had higher concentrations of TSS, TP, and VChla during low-flow conditions, compared to high-flow conditions.
- The “clear lake” endpoint at Prescott had higher concentrations of TSS and VChla, but slightly lower concentrations of TP, during low-flow conditions, compared to high-flow conditions.

Table 3. Summer means (June-September) during low-flow conditions, period of record average conditions, and high-flow conditions at two Metropolitan Council Environmental Services River Monitoring sites on Lake St. Croix: the inflow site at Stillwater, Minnesota and the outflow site at Prescott, Wisconsin, 1976-2014.

	Water quality standard	Low-flow conditions	Average conditions	High-flow conditions
Lake St. Croix Inflow at Stillwater, Minnesota				
Average flow (Qw, cfs)		4710	5490	6300
Summer average TSS (mg/L)		12.2	11.7	11.3
Summer average TP (µg/L)	40	64	63	62
Summer average VChla (µg/L)	14	25	21	19
Lake St. Croix Outflow at Prescott, Wisconsin				
Average flow (Qw, cfs)		4950	5790	6710
Summer average TSS (mg/L)		5.2	4.6	3.8
Summer average TP (µg/L)	40	47	49	50
Summer average VChla (µg/L)	14	15	12	10

CONCLUSIONS

The Lake St. Croix TMDL water quality standards for summer means (Clarity = 1.4 m, TP = 40 µg/L, and VChla = 14 µg/L) are intended to create an ecological state last seen in Lake St. Croix in the 1940s: a clear lake dominated by bottom-dwelling algae. Currently (2018), Lake St. Croix is dominated by floating algae, including blue-green algae that can produce toxic blooms (Smith et al. 2018).

The finding of alternating low-flow and high-flow conditions indicates that using decadal averages may be especially useful for evaluating progress towards Lake St. Croix TMDL goals. Given the 9-year periodicity of flow conditions, a decadal average is likely to incorporate the full range of flow conditions. Figure 21 compares the TMDL limit with the annual averages and decadal averages for the two ends of the lake (Stillwater in green and Prescott in blue) for summer mean TP and VChla concentrations, 1976-2014. Note that for both graphs, the decadal average is plotted as a running average, not at the centroid of the averaging period, but at the end of the averaging period. Thus, the decadal average does not begin until the tenth year of MCES monitoring.

Also, the TMDL limit (red line) applies to a whole-lake summer mean that should eventually plot between Stillwater and Prescott (green and blue lines, respectively) once the lake monitoring program generates enough continuous data. Despite large interannual variability partly driven by alternating flow conditions, the decadal average of TP at the two ends of the lake (Figure 21A) is decreasing, continuing the trend observed by Lafrancois et al. (2009). If the alternating flow pattern continues, 2015-2020 could experience low-flow conditions. As a result, TP concentrations, responding proportionally to flow, could continue to decrease. Based on this trajectory, the whole-lake average could possibly meet the TMDL limit for phosphorus by 2020, at least temporarily.

Inter-annual variability was high for VChla also (Figure 21B), but like the trend observed in Lafrancois et al (2009), the decadal averages are not decreasing across the 1976-2014 monitoring period. Again, if the alternating flow pattern continues, 2015-2020 could experience low-flow conditions. As a result, VChla concentrations, responding inversely-proportional to flow, could increase in the upcoming period.

Lowest Water Quality is Where Basin Runoff Enters Lake St. Croix

While there is evidence of excess phosphorus and algae throughout the length of the lake, the largest concentrations occur at Stillwater where basin runoff enters Lake St. Croix. In contrast, water quality improves downstream toward Prescott. Lake St. Croix functions well as a sediment (and sediment-borne nutrient) trap, but likely has specific, limited capability in ecological functioning. The difference between the decadal mean VChla concentrations at the two endpoints, in any given year, ranges from 9-12 µg/L. The highs and lows at Prescott (and through the whole lake) follow the highs and lows at Stillwater. This would point to a further need to investigate the sources of degraded water quality immediately upstream of Stillwater.

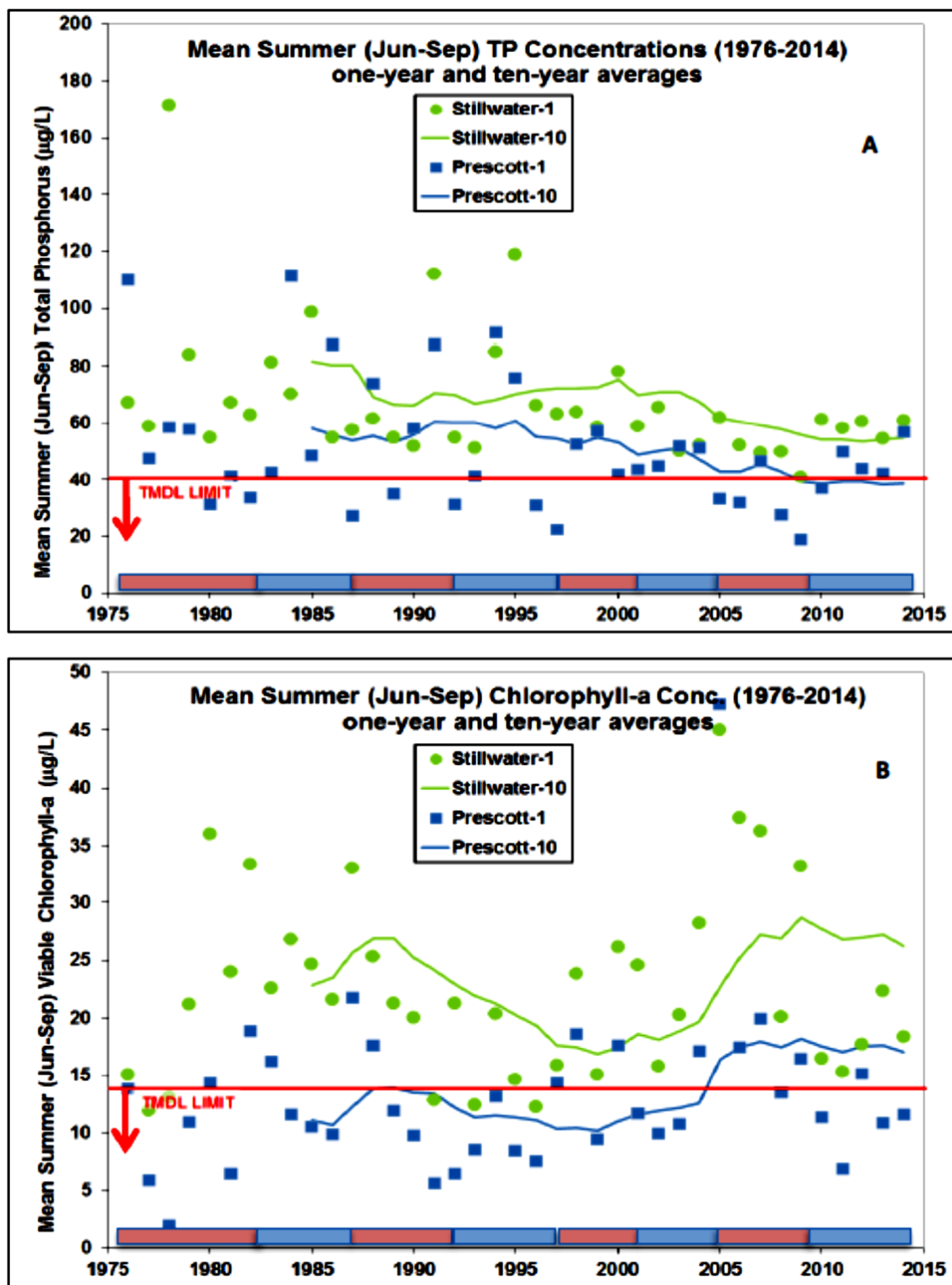


Figure 21. Annual and decadal averages of summer (June-September) concentrations at Stillwater, MN and Prescott, WI for (A) total phosphorus (micrograms per liter), and (B) viable chlorophyll a (micrograms per liter), 1976-2014. Red and blue bars indicate low-flow and high-flow conditions, respectively, as defined by moving average analyses.

Water Residence Time and Algal Blooms are Inversely Proportional to Flow

The observation that phosphorus and chlorophyll *a* concentrations respond differently to shifts in general flow condition points to a potential ecological mechanism for the decoupling of algae from nutrient supply. That is, in the presence of sufficient nutrients, algal growth rates scale with flow-dependent factors in aquatic plant growth, most likely light penetration and water residence time. High-flows carry high phosphorus concentrations, but turbid water clouded by suspended solids and high DOC shades the photic zone, and algae is transported downstream before it reproduces. In contrast, low-flows carry lower (but sufficient) phosphorus concentrations for high algal productivity in sluggish, but clear waters. Blue-green algae are well suited to the low-flow conditions because they can control their buoyancy to navigate downward into the phosphorus-rich waters below the thermocline and return back up to light in the photic zone to obtain energy for reproduction.

Looking Beyond 2020

Data presented in this report indicate that the 2020 TMDL goals will be challenging to meet because of wet and dry cycles, as well as spatial and temporal variability in the following factors: internal loading of total phosphorus, clarity, and algae – all of which are difficult to manage in the watershed. Through data analytics and lake modeling, we are gaining a better understanding of the relationship between phosphorus and chlorophyll *a* in Lake St. Croix. Although the effects of climate change were not examined in this report, climate change may alter the relationship between phosphorus and chlorophyll *a* through changes in flows, watershed loads, and lake thermal regimes. Therefore, it is important to continue monitoring flows and water quality in Lake St. Croix.

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