Limnological and Loading Response Analysis of St. Croix Flowage, Upper St. Croix River Watershed, Wisconsin

Source of image: Upper St. Croix Watershed Alliance *http://www.uscwa.org/archive.htm*. The image of the St. Croix Flowage overlaid on an historical map of Douglas County was produced with the assistance of J. Macholl, University of Wisconsin – Stevens Point.

Final Report

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PREFACE

This report was written by Mr. William F. James, Eau Galle Aquatic Ecology Laboratory (EGAEL) of the Environmental Laboratory's, Environmental Processes and Effects Division (EPED), U.S. Army Corps of Engineers - Engineer Research and Development Center (ERDC). Funding for this project was provided by U.S. Army Corps of Engineers District, St. Paul (USACE-MVD). Mr. Elliott Stefanik, USACE-MVD, was the lead project manager. The following people are gratefully acknowledged for participating in this project: Mr. Byron Karns, Department of the Interior, National Park Service, St. Croix National Scenic Riverway, and Mr. Aaron G. Carlson, Badger Technical Services, Inc., conducted field sampling and chemical analyses. Mr. Jacob Macholl, University of Wisconsin – Stevens Point, and Mr. Joe Schuler, U.S. Geological Survey, conducted flow measurements and continuous gauging of inflows to St. Croix Flowage, Ms. Nancy Turyk, University of Wisconsin – Stevens Point, was the project coordinator and lead investigator for the water quality assessment project of the St. Croix River Headwaters. Her team at UW-SP is gratefully acknowledged for providing water quality and gauging data for tributary loading analysis.

OBJECTIVES

The overall objectives of this research were to examine limnological and water quality conditions of the St. Croix Flowage, Upper St. Croix River, and forecast lake and outflow response to future changes in summer tributary phosphorus loading. The goal of this approach was to assess potential impacts that future eutrophication of St. Croix Flowage might have on loads discharged to the Upper St. Croix River System. The program *Flux* (Walker 1996) was used to estimate sediment and nutrient tributary loading. *Bathtub* was used to examine the effects of phosphorus loading increases or reduction on phosphorus and chlorophyll concentrations in the St. Croix Flowage and discharge loading to the Upper St. Croix River. Research was conducted during the summers of 2008 and 2009.

SITE DESCRIPTION AND METHODS

Watershed and lake characteristics

The St. Croix Flowage is a mesotrophic (Carlson Trophic State Index ~ 50) impoundment located in Douglas County, Wisconsin (Fig. 1). The lake has a surface area of 1913 acres, a volume of 12,554 acre-feet, and mean and maximum depths of 6.5 and 28 ft, respectively. The major tributary inflow to the lake is the St. Croix River, which converges with the Eau Claire River immediately upstream of the Flowage. The St. Croix River drains a predominantly forested watershed (66%; Macholl and Turyk 2009). Upper St. Croix Lake, located ~ 11 miles upstream of St. Croix Flowage, constitutes the headwaters of the St. Croix River and exhibits riparian development. Spring Creek also drains into the Flowage.

Tributary loading determinations

A tributary flow monitoring station was established on the St. Croix River above St. Croix Flowage at old Highway 53 in Gordon, Wisconsin, and on Lord Creek by personnel of the University of Wisconsin – Stevens Point (Macholl and Turyk 2009). Stage elevations of the river were monitored at 15-minute intervals. Mean daily stage elevations were converted to volumetric flow (cubic meters per second; cms) using stage-discharge relationships generated under different flow regimes. Tributary base flow and event water sampling were conducted by the University of Wisconsin – Stevens Point in 2008 and 2009 for determination of total suspended solids, total nitrogen, Kjeldahl nitrogen (i.e., organic nitrogen), ammonium, nitrate+nitrite, total phosphorus, and soluble reactive phosphorus using analytical methods described in Macholl and Turyk (2009). Seasonal (i.e., May through September) loadings were estimated using the computer model *Flux* (Walker 1996).

Flowage and discharge monitoring

Sampling stations were established in the western (station 10; ~ 5 ft deep) and eastern (station 20; ~ 12 ft deep) region of the lake for biweekly sampling during May through early November of 2008 and 2009 (Fig. 1). In situ profiles of temperature, dissolved oxygen, pH, and conductivity were collected at ~1-m intervals at each station using a Hydrolab Quanta monitor calibrated against known standards. Secchi disk transparency was measured using an alternating black and white, 10-cm, disk. Water samples were collected at 1-m depth intervals in 2008. An integrated sample that combined water over the entire vertical water column was collected at each station in 2009. Additional surface samples were collected at the St. Croix Flowage discharge (station 30) and at the St. Croix River near Scott Lake Bridge (station 40; Fig. 1), during the summer of 2008. Samples were analyzed for total suspended and volatile solids, total nitrogen, ammonium, nitrate+nitrite, total phosphorus, soluble reactive phosphorus, chloride, and chlorophyll a. For total suspended and volatile solids, suspended material retained on a precombusted glass fiber filter (Gelman A/E) was dried to a constant weight at 105 ^{o}C and then combusted at 500 ^{o}C (APHA 1998). Samples for total nitrogen and phosphorus were predigested with potassium persulfate according to Ameel et al. (1993) before analysis. Ammonium, nitrate+nitrite, and soluble reactive phosphorus samples were filtered through a 0.45 μm filter prior to analysis (Millipore MF). Nitrogen and phosphorus was determined colorimetrically on a Lachat QuikChem automated water chemistry system (Hach Company, Loveland, CO). Chlorophyll was determined via a fluorometric technique following extraction in a 1:1 solution of acetone and dimethyl sulfoxide (Welschmeyer 1994). The Carlson Trophic State Index (TSI; Carlson 1977) was estimated for St. Croix Flowage using the computer program *Bathtub* (Walker 1996). Mean Secchi transparency values and mean concentrations of total phosphorus and chlorophyll estimated over the period May through September of both years were used in the calculation.

Load response modeling

The computer model *Bathtub* (Walker 1996) was used as a management tool to forecast the trophic response of St. Croix Flowage and the discharge load to reductions or increases in tributary inflow phosphorus loading. Concentrations of chlorophyll and total phosphorus averaged for the two in-lake stations over the period May through September, 2008, were used as summer conditions for input into the model. Tributary phosphorus loadings were increased and decreased incrementally by nearly 100% of current phosphorus loading conditions to forecast lake and discharge response.

RESULTS

Hydrology and tributary loading

Annual precipitation of 29 and 24 inches in 2008 and 2009, respectively, was below the annual average of 32 inches for the region. Summer (May-September) precipitation was also greater in 2008 versus 2009 (Fig. 2). Seasonally, rain events greater than 1 inch occurred in early May, early June, mid-September, and early October, 2008 (Fig. 3). Rainfall intensity was lower in May and June, 2009 (Fig. 3). Events greater than 1 inch occurred in mid-July, mid-August, and late September, 2009. Flows for the St. Croix River above St. Croix Flowage increased in conjunction with precipitation events during both years (Fig. 3). Flow declined in July and August, 2008, as a result of lower rainfall. In contrast, St. Croix River flow was higher during July and August, 2009, and coincided with two precipitation events that exceeded 1 inch during this period. Even though precipitation was minimal, flow was relatively high in May, 2009, which may be due to snowmelt contributions. Overall, The St. Croix River dominated mean summer hydrological inputs to St. Croix Flowage (Table 1). Lord Creek inputs were minor in comparison. Mean summer St. Croix River flow was slightly higher in 2009 compared to 2008, despite lower rainfall during the former summer (Table 1). The theoretical water residence time (i.e., the length of time it takes to completely refill the lake) of the Flowage was ~ 43 days for both summers.

Summer inflow constituent loading was generally similar in 2008 and 2009 with the St. Croix River dominating inputs to St. Croix Flowage (Table 2). Total suspended solids loading was relatively low during both years as flow-weighted concentrations were only slightly above detection limits. Kjeldahl nitrogen accounted for most of the total nitrogen load to the Flowage. Nitrate+nitrite and ammonium loading and flow-weighted concentrations were much lower versus Kjeldahl nitrogen. Flow-weighted total phosphorus concentrations of loads entering the Flowage were modest compared to other watersheds (Table 3) in Western Wisconsin and ranged between 0.031 and 0.037 mg/L. The soluble phosphorus concentration of St. Croix River loads was low at less than ~ 0.020 mg/L. However, this fraction represented approximately half of the total phosphorus load and was available for algal uptake. Thirty-five percent of the summer total phosphorus loading was retained in the Flowage.

Flowage Water Quality

Vertical temperature stratification was minor in the Flowage during the summer of both years, suggesting generally mixed conditions. In addition, dissolved oxygen concentrations were high throughout the water column. Surface water temperatures reached a maximum of ~ 24 ^{o}C during June through August (Fig. 4). pH ranged between 7.3 and 9.7. Higher pH was presumably a result of photosynthesis by aquatic macrophytes and algae. Peaks in pH were observed in late June, 2008, and in May and August, 2009. Alkalinity concentrations of ~52 mg/L indicated moderately buffered conditions with respect to acid-neutralizing capabilities.

Total suspended and volatile solids concentrations were greater in 2009 than 2008 (Fig. 5). In particular, peaks observed in May and August, 2009, were associated with similar increases in chlorophyll concentration, suggesting that total suspended solids were comprised primarily of algae. Volatile solids represented ~ 68% of the total solids, indicating a dominance of organic matter, probably as algae. With the exception of peaks in 2009, chlorophyll concentrations were usually below 10 μg/L, indicating low bloom frequency. Total phosphorus concentrations were usually less than 0.030 mg/L during both study years (Fig. 6). A peak in total phosphorus concentration of greater than 0.050 mg/L observed in June, 2008, coincided with a period of high flow from the St. Croix River, suggesting influences from runoff and loading. Soluble phosphorus concentrations were usually less than 0.01 mg/L during the summer, indicating that most of the phosphorus in the water column was in particulate form, apparently as algal biomass. Similar to loading patterns, most of the total nitrogen was in an organic form (Fig. 7). In contrast, nitrate+nitrite and ammonium concentrations were very low during both summers. Chloride concentrations were similar for station 10 and 20 during both years (Fig. 8). In addition, inflow chloride concentrations were similar to those in the lake in 2009. Dilution via groundwater inputs to the lake that were low in chloride concentration might result in lower chloride concentrations in the lake versus the inflow. However, chloride trends suggested that groundwater inputs were low relative to other hydrological inputs.

Mean summer concentrations for each year are shown in Table 4. Overall, mean total phosphorus and chlorophyll concentrations were relatively low and indicative of mesotrophic conditions (i.e., moderately clear). Secchi disk transparency was high and essentially equivalent to the water column depth at station 10 and 20, suggesting ample light penetration to the lake bottom for aquatic plant growth. The trophic state index of the Flowage ranged between 47 and 52 (Table 5), reflecting good water quality conditions (Fig. 9).

Water quality in the St. Croix River downstream of St. Croix Flowage

Particulate constituent concentrations tended to be greatest in the discharge of St. Croix Flowage and decline downstream (Fig. 10). An exception was a peak in total and volatile suspended solids at station 40 in May, 2008, which probably coincided with elevated flows and loading from Moose Creek, located immediately upstream of station 40. A similar pattern was observed for total and Kjeldahl nitrogen during periods of higher flow in May and September, 2008 (Fig. 12). Chlorophyll concentrations declined markedly between station 30 and 40 during July through September, 2008, suggesting sedimentation or assimilation by herbivores. In contrast, soluble constituents did not exhibit longitudinal trends (Fig. 11 and 12). Mean summer concentrations of ammonium, nitrate+nitrite, and soluble phosphorus were similar for stations 30 and 40 (Table 6), suggesting little uptake or recycling of soluble constituents. Instead, these loads appeared to be transported downstream with little or no transformation. Mean summer chloride concentrations were similar at both stations, indicating minimal dilution via groundwater.

Bathtub modeling and lake response to loading scenarios

Bathtub models used for the prediction of total phosphorus and chlorophyll response under differing tributary P loading scenarios are shown in Table 7. Model coefficients were calibrated against data collected during the summer of 2008 since this was the more complete data set. The phosphorus calibration coefficient was high at 2.24, but fell within the range of 0.5 to 2.5 found for reservoirs in the United States (Walker 1996). The higher calibration value may be associated with the occurrence of abundant submersed aquatic vegetation in St. Croix Flowage that probably enhanced phosphorus sedimentation. St. Croix Flowage water quality response was evaluated for scenarios of both increased and decreased phosphorus loading over 2008 conditions. It was further assumed that phosphorus loading variation resulted primarily from changes in phosphorus concentration versus changes in flow.

Simulated decreases in tributary phosphorus loading resulted in predicted decreases in the average summer concentration of total phosphorus and chlorophyll of the surface waters and increases in Secchi transparency (Fig. 13). For instance, a 50% reduction in summer tributary phosphorus loading resulted in a predicted 42% decrease in total phosphorus (i.e., to 0.012 mg/L) and a 53% decrease in chlorophyll concentration (i.e., to 2.68 μg/L) in the Flowage. In contrast, simulated phosphorus loading increases due, for instance, to increased phosphorus runoff in the watershed, resulted in substantial predicted increases in total phosphorus and chlorophyll concentrations and decreases in Secchi transparency in the Flowage. A simulated 50% increase in phosphorus loading over 2008 conditions resulted in a predicted 35% increase in total phosphorus (i.e., to ~ 0.028 mg/L) and a 52% increase in chlorophyll concentration (i.e., to 8.69 μg/L). However, model output suggested that the trophic state index would remain below 60 (TSI > 60 considered eutrophic) even at the highest phosphorus loading levels (Fig. 14). Watershed loading-induced increases in lake total phosphorus and chlorophyll would result in greater discharge loads to the St. Croix River below the Flowage as illustrated in Fig. 15.

DISCUSSION

St. Croix Flowage exhibited very good water quality conditions during the summer of 2008 and 2009, indicating a mesotrophic, clear water state. External loading appeared to be the primary phosphorus source to the Flowage as Macholl et al. (2009) reported that internal sediment phosphorus release is negligible. Chlorophyll concentrations were low and light penetration was very good, as Secchi transparency measurements generally coincided with the lake bottom.

Modeling results suggested that St. Croix Flowage water quality is susceptible to phosphorus loading increases. Chlorophyll concentrations would essentially double and the trophic state index would approach eutrophic conditions (see Fig. 9) if phosphorus loading increased by 100% over current conditions. Not simulated in *Bathtub* is the potential for increased internal phosphorus loading from sediment retained in the Flowage over time if external phosphorus loads increase. Declines in Secchi transparency with increased phosphorus loading could impact growth and reproduction of submersed aquatic macrophytes in the system. A healthy native plant community is important for fish and macroinvertebrates.

Increased phosphorus loading to St. Croix Flowage would also result in elevated phosphorus discharge to the St. Croix River. Current discharge phosphorus concentrations are ~ 0.020 to

0.025 mg/L. A doubling of phosphorus loading to the system would result in a predicted increase in discharge phosphorus concentrations to 0.040 mg/L or greater. Nutrient uptake appears to be minor under current conditions in the St. Croix River below the Flowage. An unknown is what effect increased nutrient loading might have on nutrient spiraling and uptake length (i.e., transformation of soluble nutrients to particulate forms via assimilation or adsorption) in the river. If uptake is relatively low, nutrient loads may be transported downstream with little transformation. Conversely, the St. Croix River may have capacity to retain a portion of the load if watershed runoff increases in the future, lessoning loading impacts to downstream locations.

REFERENCES

Ameel, J.J., Axler, R.P., and Owen, C.J. 1993. Persulfate digestion for determination of total nitrogen and phosphorus in low nutrient water. Am. Environ. Lab. (October, 1993):8-10.

APHA (American Public Health Association). 1998. Standard Methods for the Examination of Water and Wastewater. 20th ed. American Public Health Association, American Water Works Association, Water Environment Federation.

Carlson, R.E., 1977. A trophic state index for lakes. Limnology and Oceanography 22:361-36.

Macholl, J., and Turyk, N. 2009. Water quality assessment of the St. Croix headwaters, Douglas and Bayfield Counties, Wisconsin. Progress report to the Wisconsin Department of Natural Resources, February, 2009.

Macholl, J., Turyk, N., McGinley, P, and Clancy, K. 2009. St. Croix Headwaters Watershed Project. UW-SP Quarterly Report of Activities: July-September 2009. http://www.uscwa.org/documents/UW-SP%20Third%20Quarter%202009%20Watershed%20Report.pdf

Walker, W.W., 1996. Simplified procedures for eutrophication assessment and prediction: User manual. Instruction Report W-96-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Welschmeyer, N.A. 1994. Fluorometric analysis of chlorophyll a in the presence of chlorophyll b and pheopigments. Limnol. Oceanogr. 39:1985-1992.

Table 1. Mean summer (May-September) flow, precipitation, and lake residence time.

Year	Inflow St. Croix (ft^3/s)	Inflow Lord (ft^3/s)	Direct Precip (ft^3/s)	Lake Residence Time (days)
2008	133.4	3.2	9.0	43.5
2009	140.5	1.7	5.9	42.7

Table 2. Summer constituent loading and flow-weighted mean concentration for the St. Croix River above St. Croix Flowage and Lord Creek[1]. CV = coefficient of variation.

Constituent	Inflows					
	St. Croix River			Lord Creek		
	(kg/d)	(mg/L)	(CV)	(kg/d)	(mg/L)	(CV)
2008						
Total Suspended Sediment	580.7	1.8	0.17	60.7	8.8	0.05
Total Nitrogen	129.2	0.396	0.08	10.5	1.52	0.13
Total Kjeldahl Nitrogen	109.1	0.334	0.06	8.9	1.28	0.1
Ammonium-N	8.1	0.025	0.10	0.07	0.01	0.11
Nitrate-nitrite-N	14.6	0.045	0.20	0.34	0.05	0.42
Total Phosphorus	11.6	0.035	0.08	0.26	0.037	0.11
Soluble Reactive Phosphorus	6.6	0.02	0.07	0.06	0.009	0.16
2009						
Total Suspended Sediment	610.6	1.9	0.16	18.8	4.6	0.31
Total Nitrogen	120.8	0.351	0.06	6.2	1.52	0.13
Total Kjeldahl Nitrogen	107.3	0.314	0.06	6.0	1.47	0.15
Ammonium-N	7.0	0.02	0.08	0.13	0.03	0.23
Nitrate-nitrite-N	12.5	0.036	0.18	0.20	0.05	0.42
Total Phosphorus	10.6	0.031	0.05	0.15	0.037	0.11
Soluble Reactive Phosphorus	4.9	0.014	0.12	0.04	0.009	0.16

[1] Water quality and flow data were provided by the University of Wisconsin – Stevens Point.

Table 3. A comparison of flow-weighted total phosphorus (P) concentration for various tributaries in western Wisconsin.

Tributary	Receiving Reservoir	Forested watershed (%)	Year	Total P (mg/L)	Soluble P (mg/L)
St. Croix River @ Gordon, WI	Gordon Flowage	66	2008	0.035	0.020
Eau Claire River @ County M., WI	Mead Lake	23	2002	0.120	0.063
Otter Creek, WI	Otter Lake	32	2001	0.087	0.045
Yellow River @ County XX, WI	Lake Wissota	36	2001	0.093	0.036
Jump River, WI	Lake Holcombe	43	1995	0.080	
Flambeau River, WI	Lake Holcombe	55	1995	0.040	
Yellow River @ County MM, WI	Chequamagon Flowage	59	2001	0.040	0.017
Chippewa River, WI	Lake Holcombe	62	1995	0.050	

Table 4. Mean summer constituent water quality concentrations in St. Croix Flowage in 2008 and 2009.

Consituent	2008	2009
Total alkalinity (mg/L)	51.2	52.1
Total suspended solids (mg/L)	1.2	2.7
Total volatile solids (mg/L)	0.8	1.9
Chlorophyll (ug/L)	5.6	6.5
Total nitrogen (mg/L)	0.372	0.425
Kjeldahl nitrogen (mg/L)	0.358	0.401
Ammonium (mg/L)	0.02	0.014
Nitrate-nitrite (mg/L)	0.014	0.018
Total phosphorus (mg/L)	0.021	0.028
Soluble phosphorus (mg/L)	0.004	0.004
Chloride (mg/L)	3.50	2.83
Secchi transparency (m)	2.23	1.88
pH	8.37	8.13

Table 5. Carlson (1977) Trophic State Index (TSI) for St. Croix Flowage in 2008 and 2009.

TSI	2008	2009
$TSI_{Phosphorus}$	48.1	52.2
$TSI_{Chlorophyll}$	47.7	49.0

Table 6. Mean summer constituent water quality concentrations in the St. Croix River downstream of Gordon Dam in 2008 and 2009.

Consituent	station 30	station 40
Total alkalinity (mg/L)	48.3	46.8
Total suspended solids (mg/L)	1.5	2.6
Total volatile solids (mg/L)	1	1.1
Chlorophyll (ug/L)	5.8	2.2
Total nitrogen (mg/L)	0.411	0.484
Kjeldahl nitrogen (mg/L)	0.400	0.468
Ammonium (mg/L)	0.013	0.010
Nitrate-nitrite (mg/L)	0.011	0.016
Total phosphorus (mg/L)	0.026	0.020
Soluble phosphorus (mg/L)	0.005	0.005
Chloride (mg/L)	2.83	2.78

Table 7. *Bathtub* models and coefficients.

Variable	Option	Model	Coefficient
Total phosphorus	1	2nd order available P	2.24
Chlorophyll	5	Jones and Bachman	0.826
Transparency	3	versus total P	1
Longitudinal dispersion	1	Fischer-numeric	1

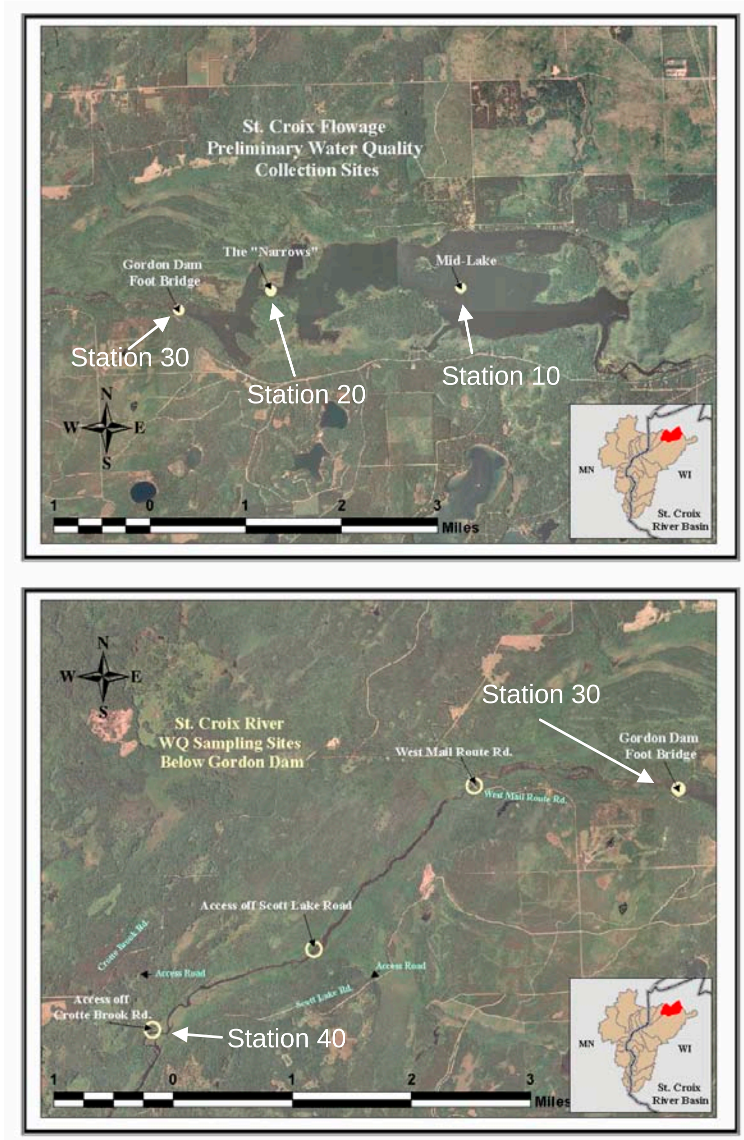


Fig. 1. Station locations in St. Croic Flowage and the St. Croix River below Gordon Dam.

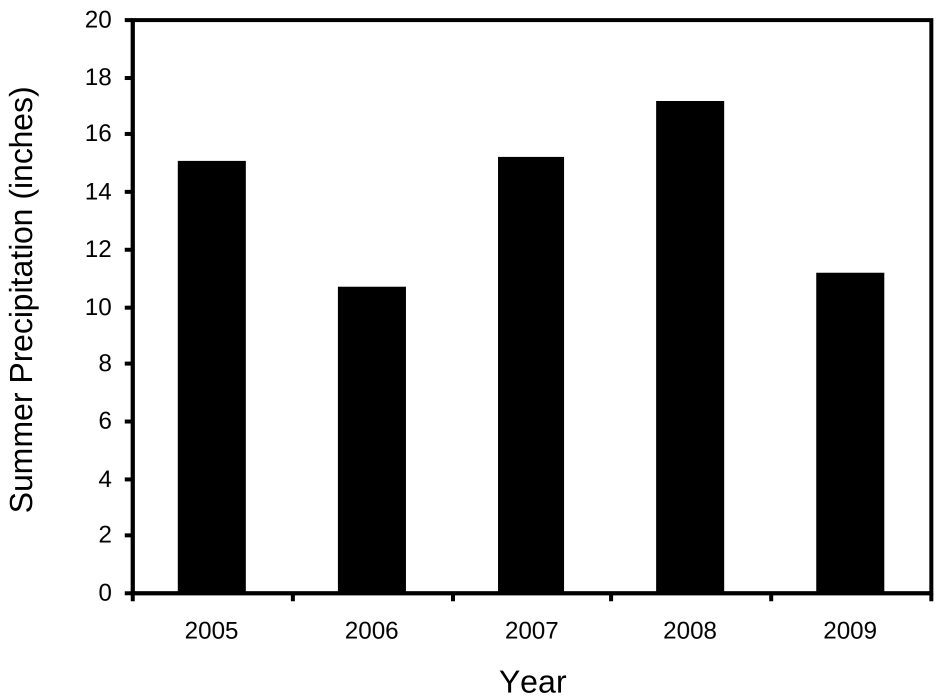


Fig. 2. Summer precipitation (total inches; May and September) between 2005 and 2009.

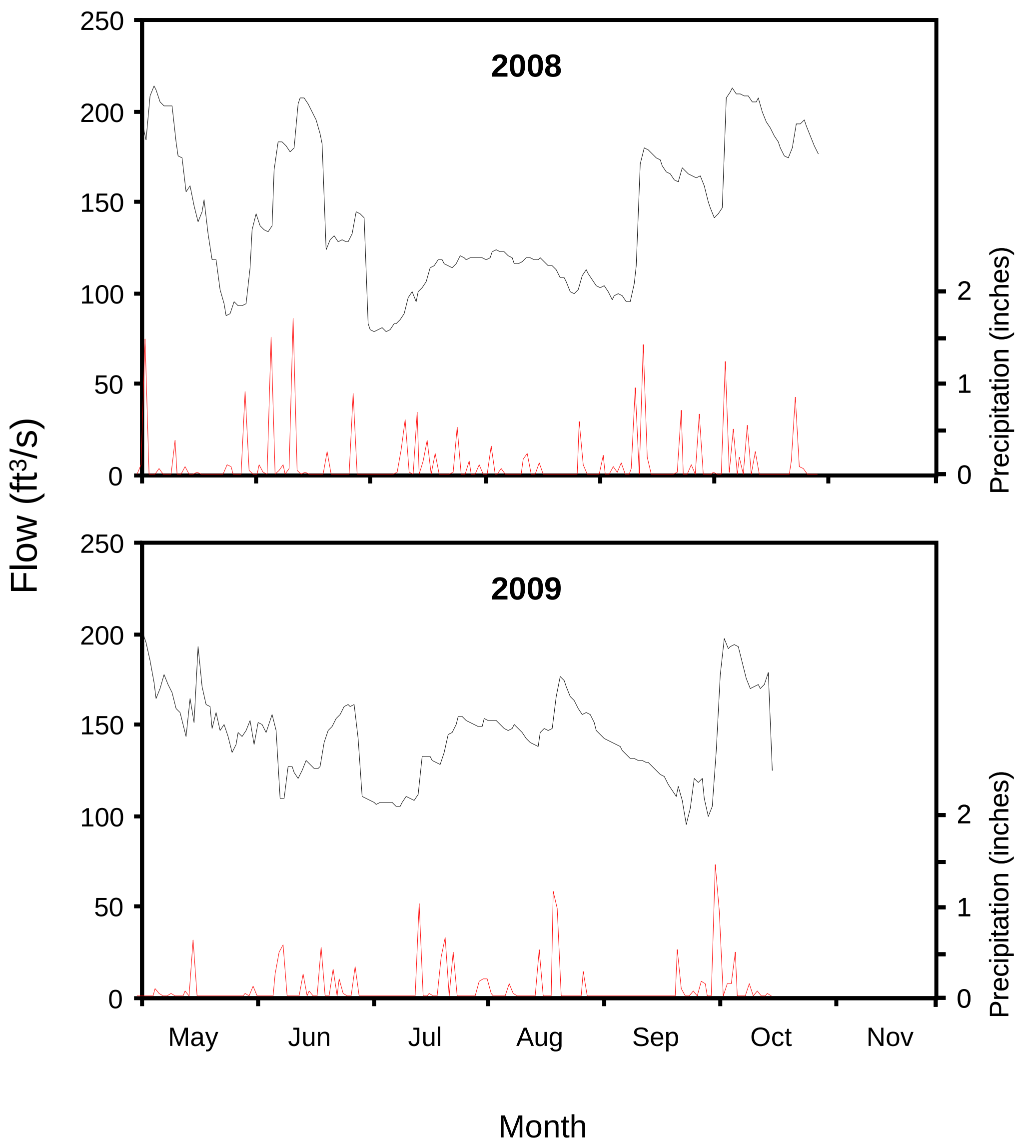


Fig. 3. Seasonal variations in St. Croix River flow above St. Croix Flowage and daily precipitation.

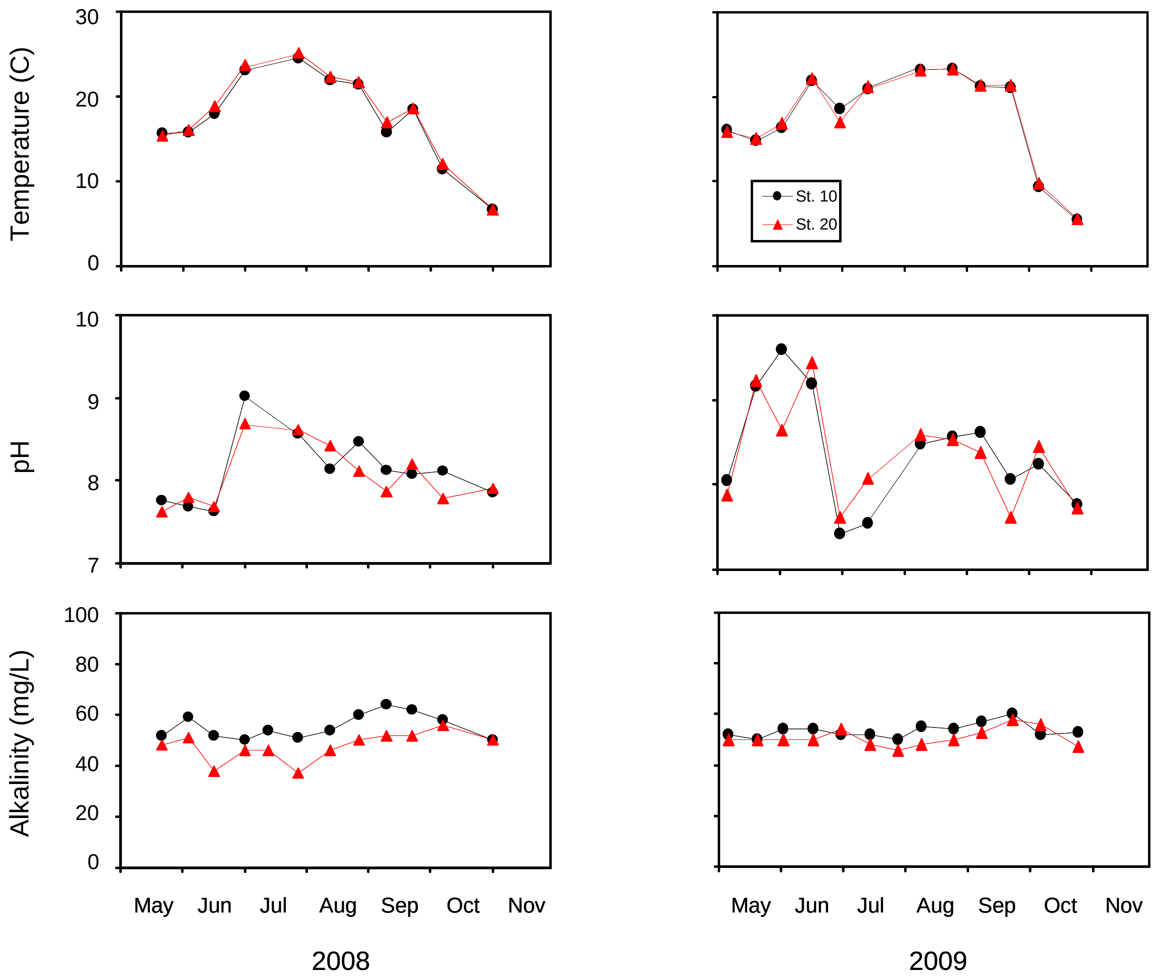


Fig. 4. Seasonal variations in surface water temperature, pH, and alkalinity in St. Croix Flowage.

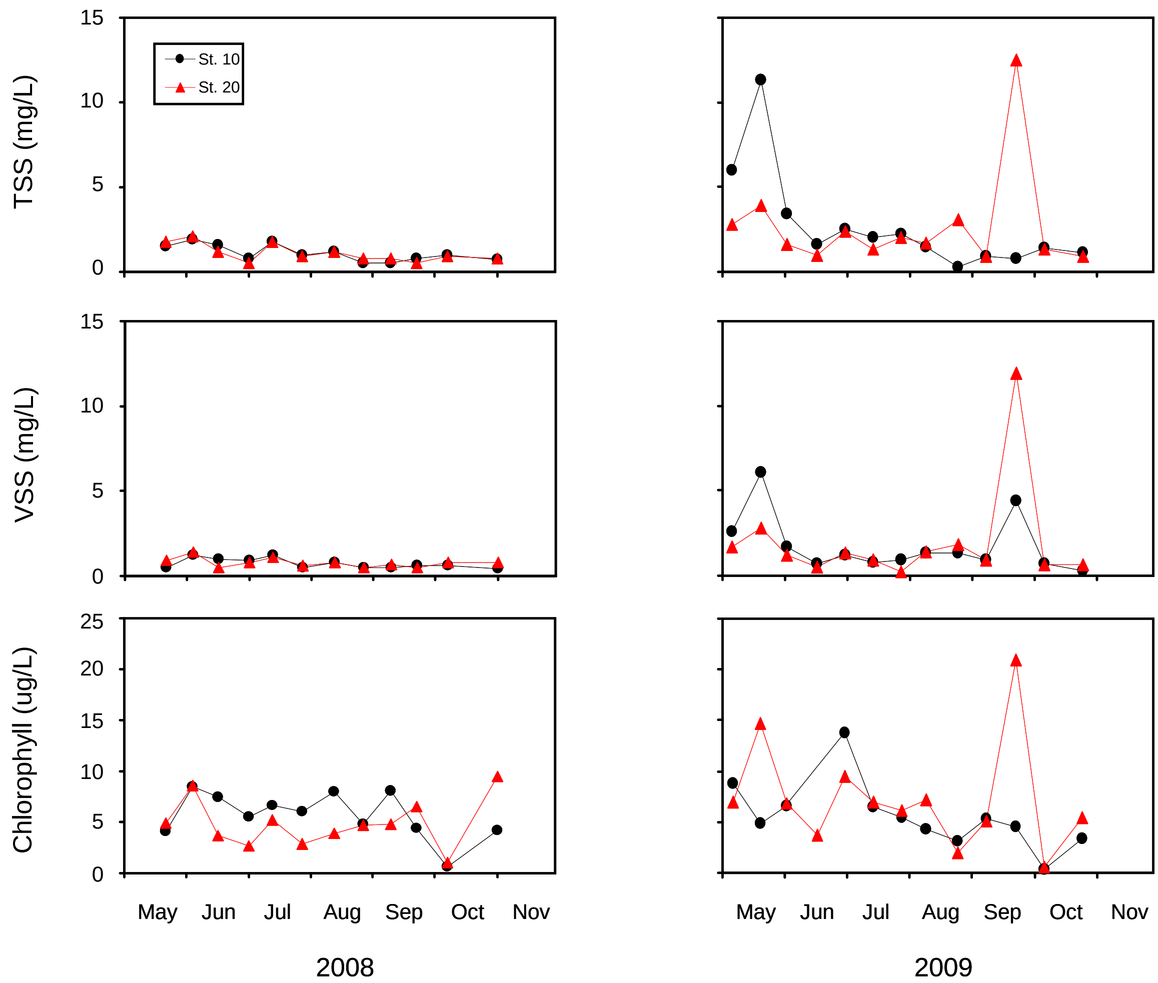


Fig. 5. Seasonal variations in surface total suspended solids (TSS), volatile suspended solids (VSS), and chlorophyll in St. Croix Flowage.

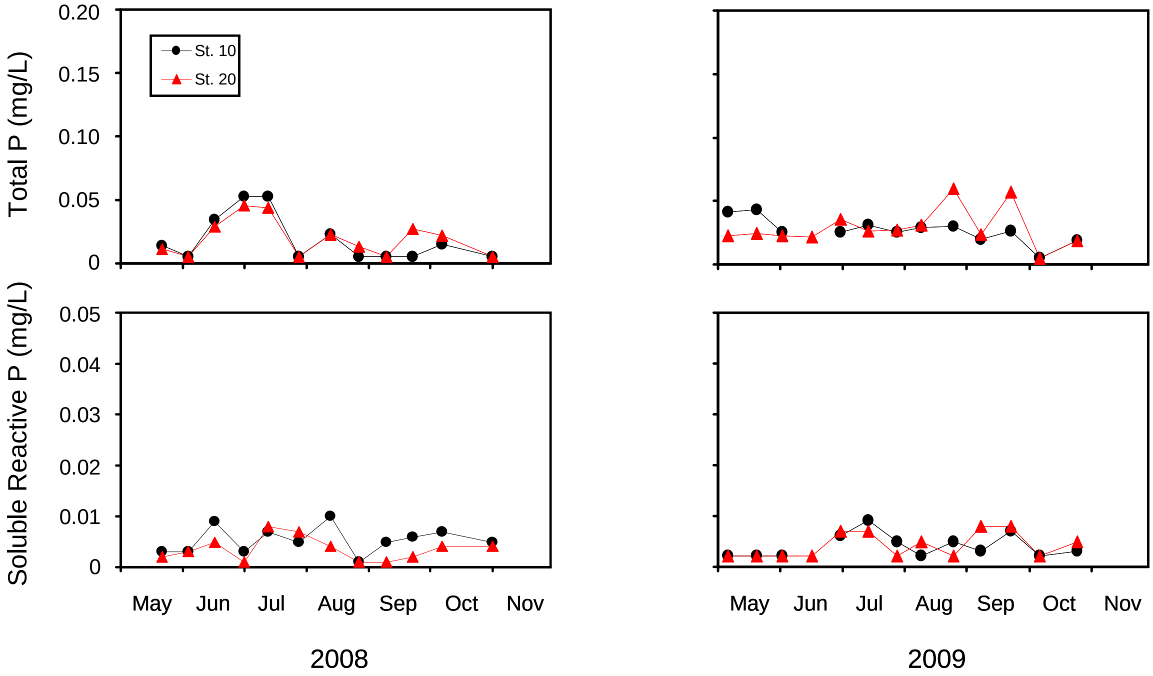


Fig. 6. Seasonal variations in surface total phosphorus (P) and soluble reactive P (i.e., soluble P) in St. Croix Flowage.

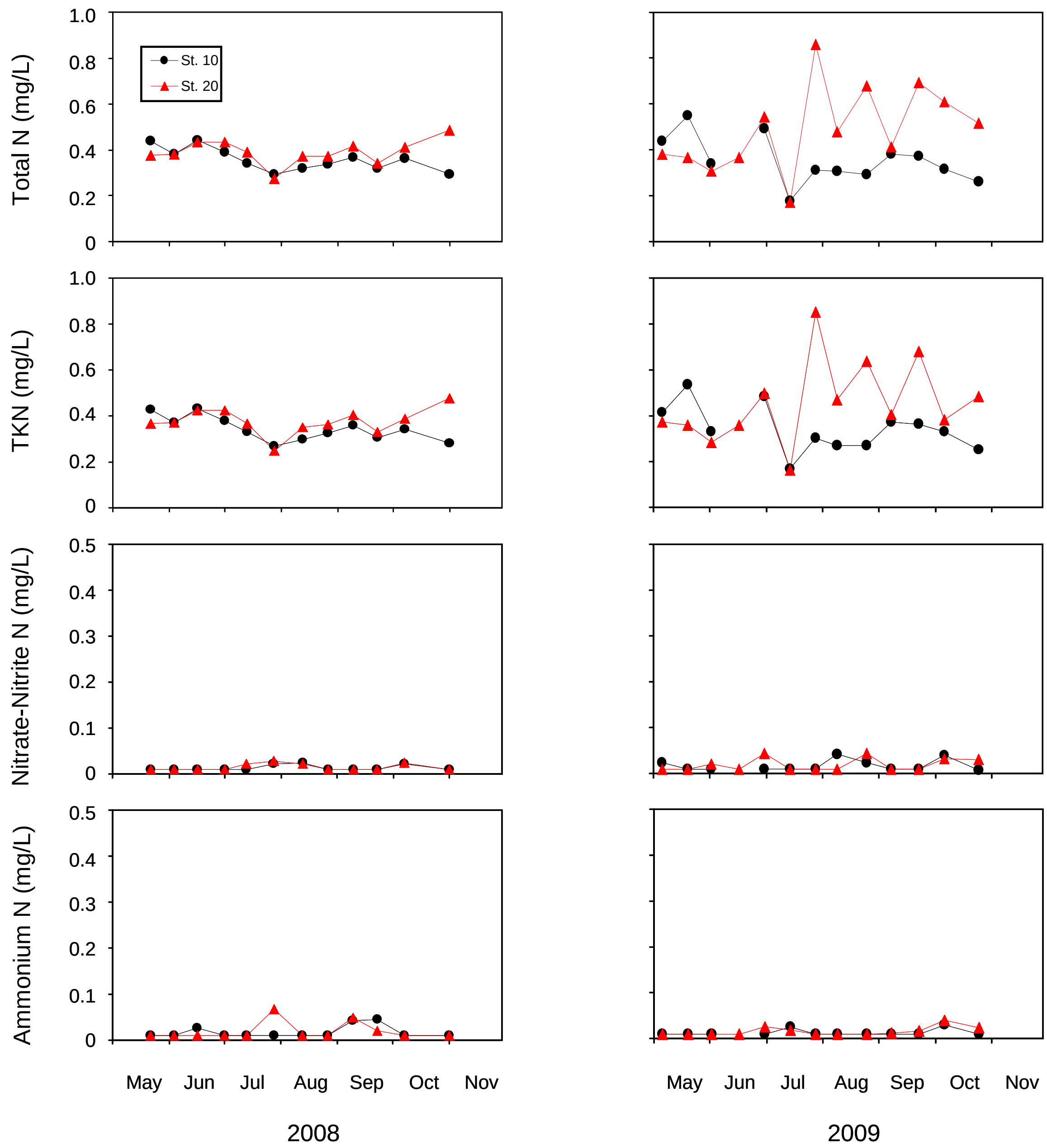


Fig. 7. Seasonal variations in surface total nitrogen (N), total Kjeldahl N (TKN), nitrate+nitrite, and ammonium in St. Croix Flowage.

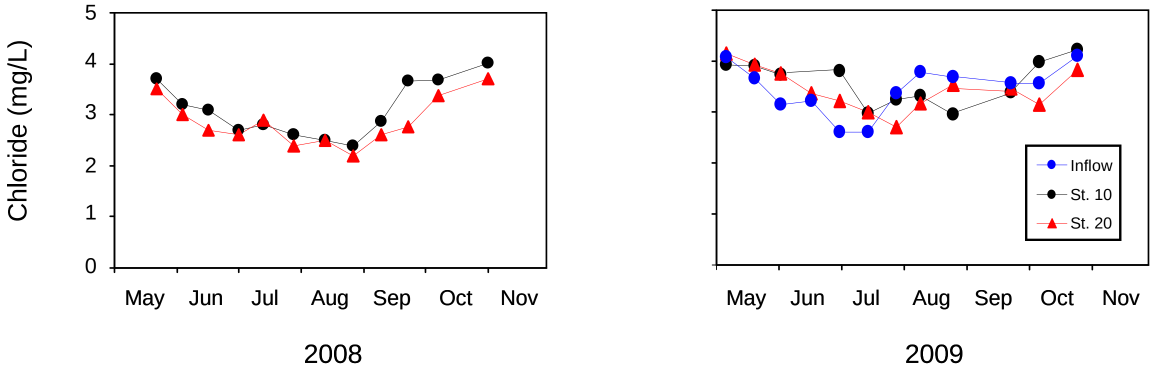
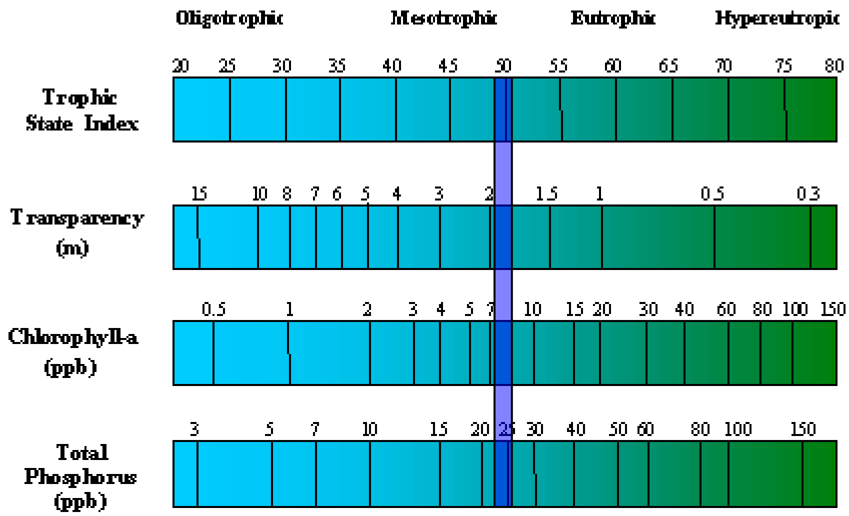


Fig. 8. Seasonal variations in surface chloride in St. Croix Flowage.



http://www.pca.state.mn.us/water/glossary/tsi.html

Fig. 9. Conceptual diagram of relationships between trophic state index values and concentrations of chlorophyll, total phosphorus, or transparency depth. Transparent blue line indicates trophic state index relationships for St. Croix Flowage.

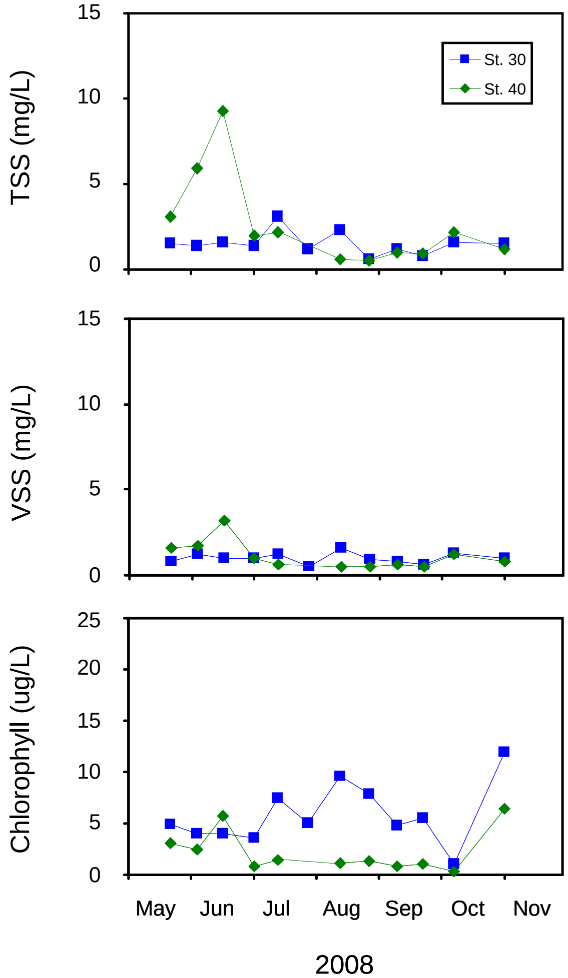


Fig. 10. Seasonal variations in total suspended solids (TSS), volatile suspended solids (VSS), and chlorophyll in the St. Croix River downstream of St. Croix Flowage.

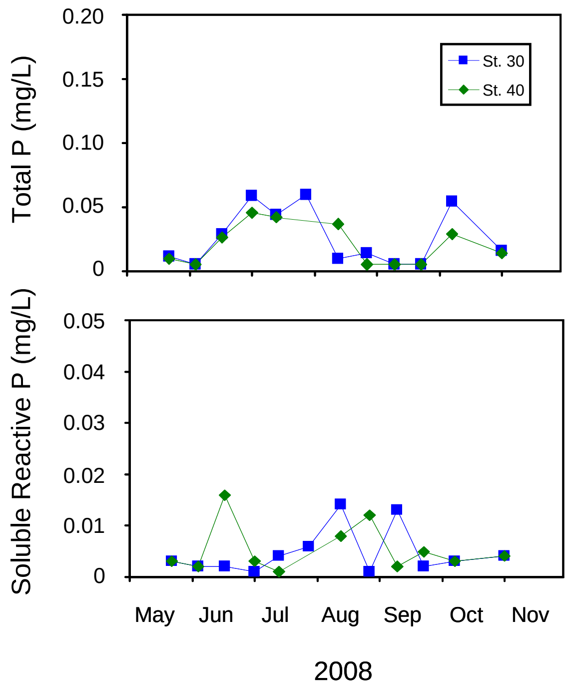


Fig. 11. Seasonal variations in surface total phosphorus (P) and soluble reactive P (i.e., soluble P) in the St. Croix River downstream of St. Croix Flowage.

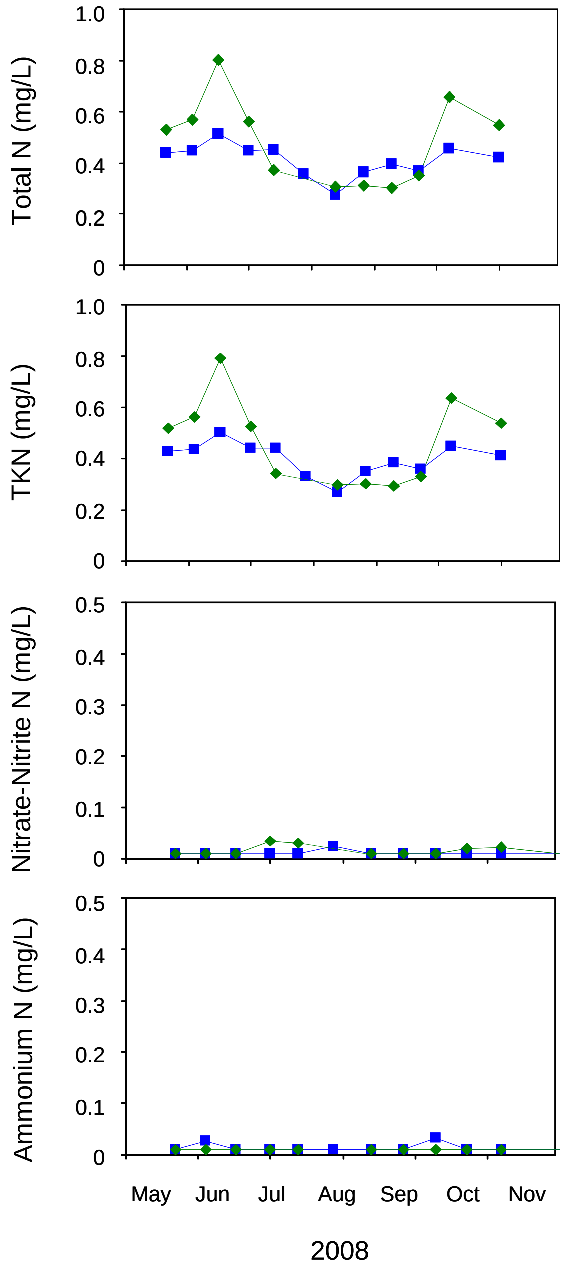


Fig. 12. Seasonal variations in surface total nitrogen (N), total Kjeldahl N (TKN), nitrate+nitrite, and ammonium in the St. Croix River downstream of St. Croix Flowage.

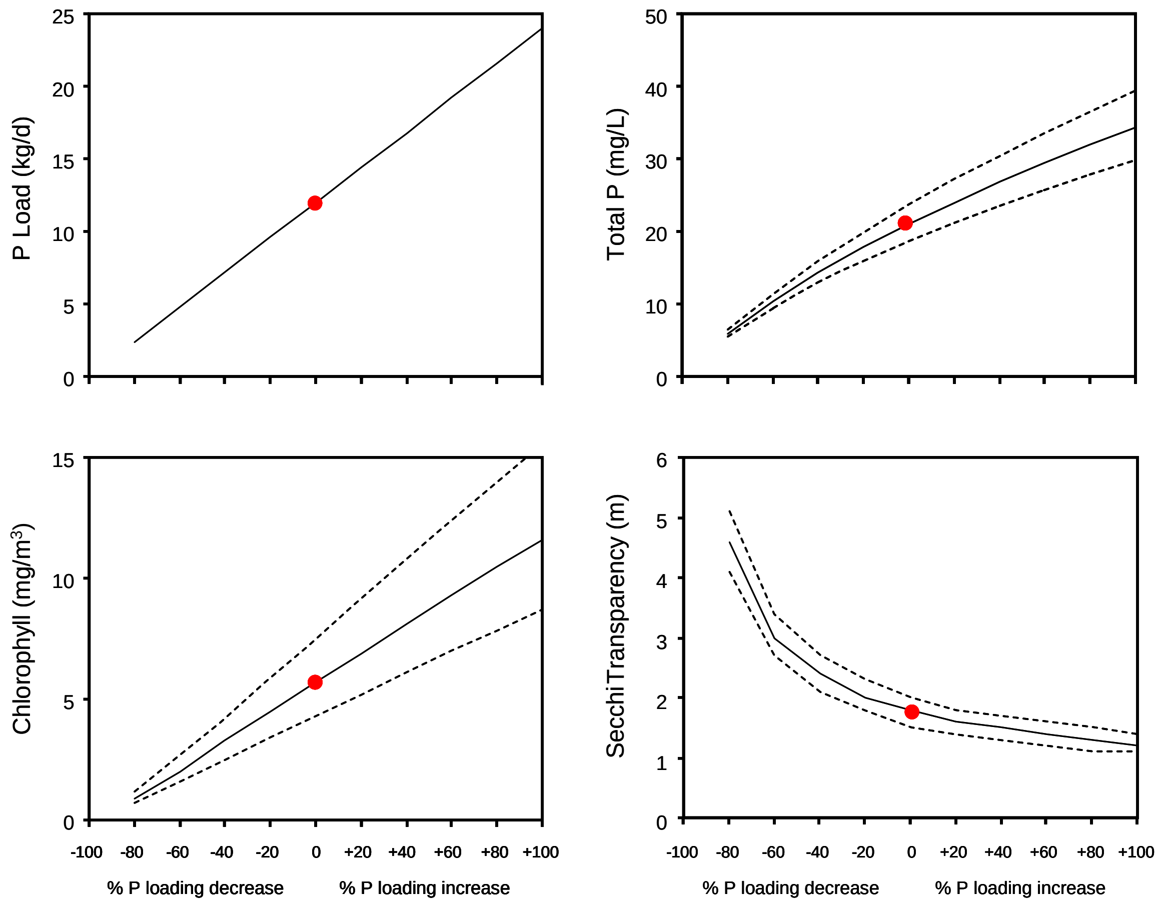


Fig. 13. Bathtub model output of predicted changes in total phosphorus (P), chlorophyll, and Secchi transparency as a function of increases or decreases in 2008 P loading conditions to St. Croix Flowage. Dotted lines denote 95% confidence intervals. Red circles represent current conditions.

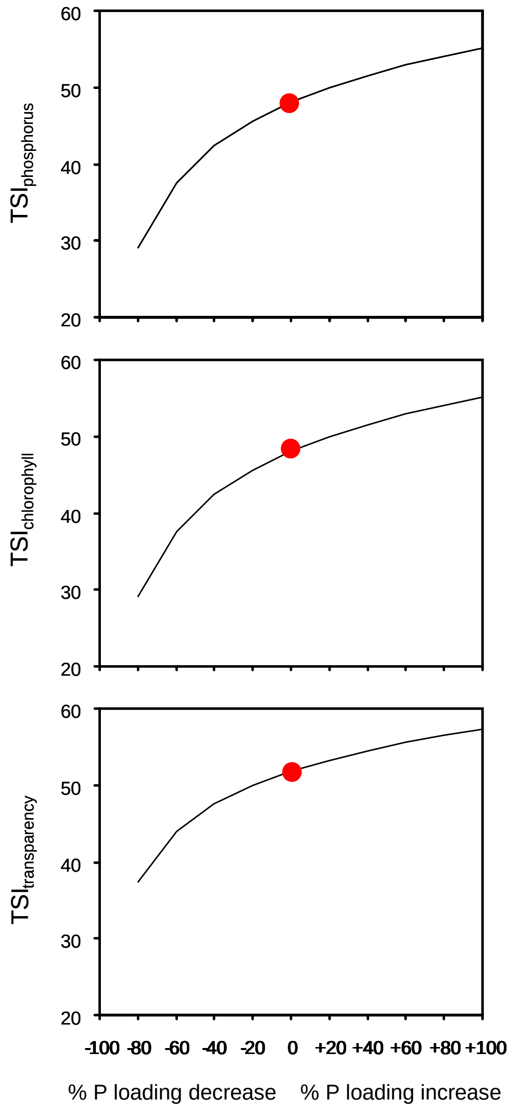


Fig. 14. Bathtub model output of predicted changes in trophic state index (TSI) values based on total phosphorus, chlorophyll, and Secchi transparency as a function of increases or decreases in 2008 P loading conditions to St. Croix Flowage. Red circles represent current conditions.

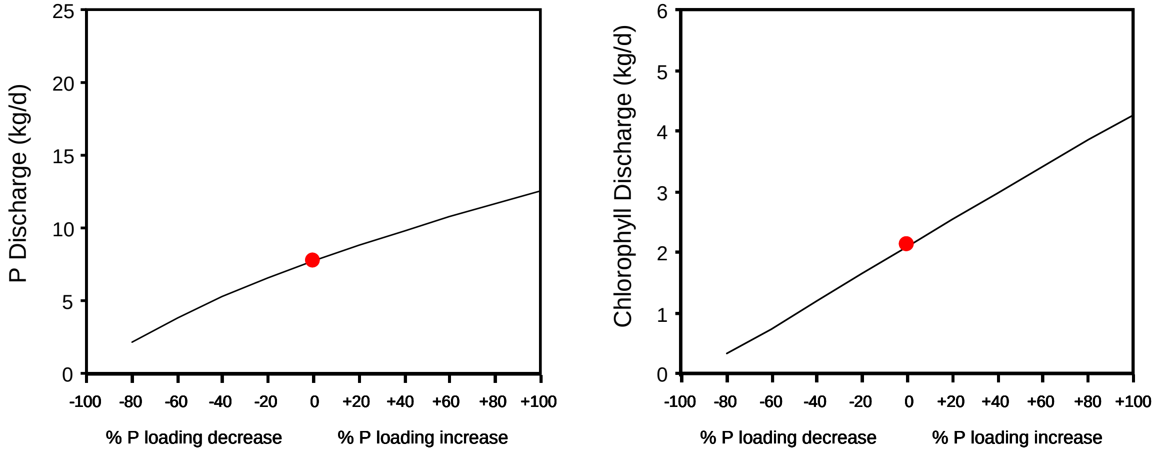


Fig. 15. Bathtub model output of predicted changes in phosphorus (P) and chlorophyll discharge loads from St. Croix Flowage to the St. Croix River as a function of increases or decreases in 2008 P loading conditions to St.Croix Flowage. Red circles represent current conditions.