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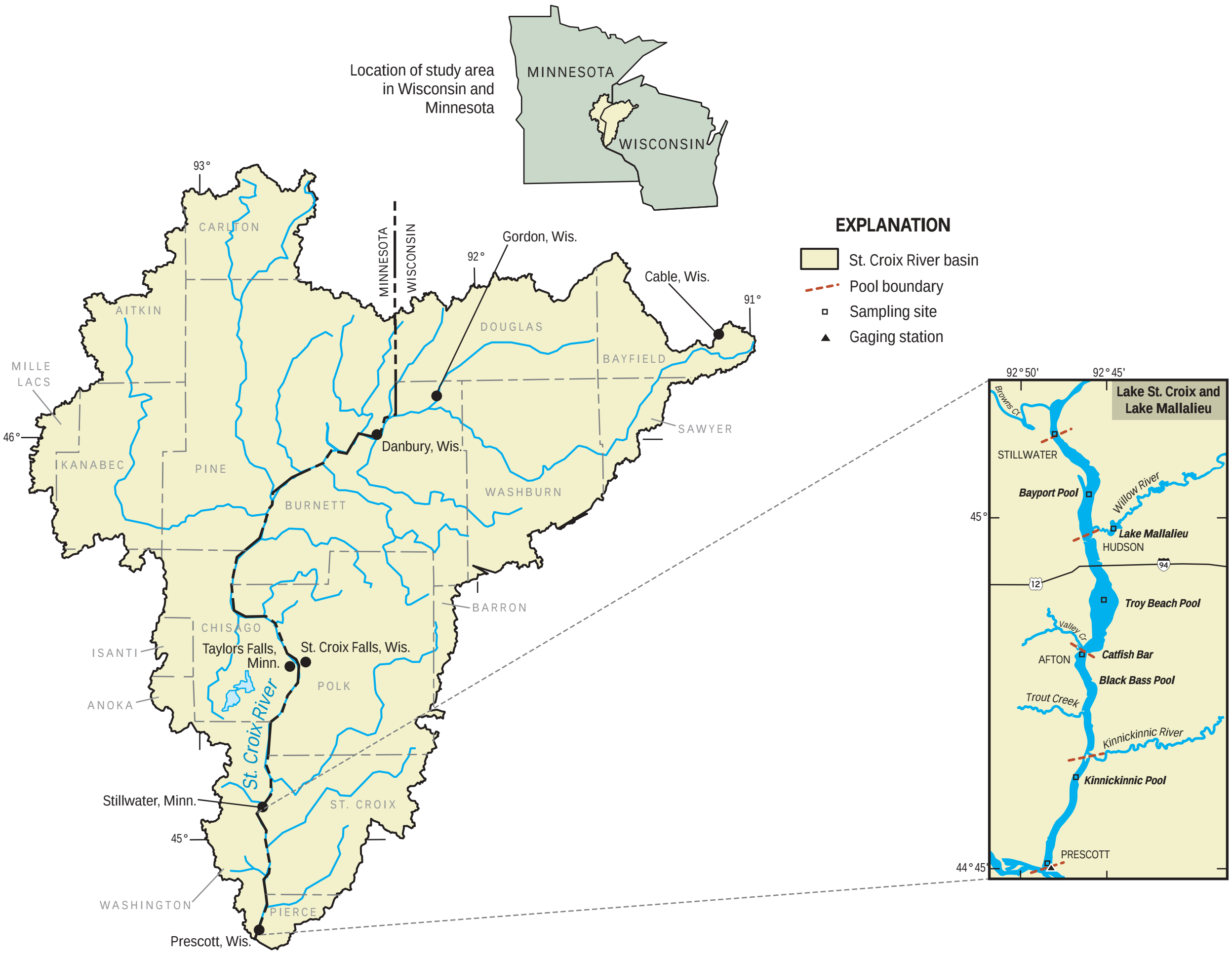
Response of the St. Croix River Pools, Wisconsin and Minnesota, to Various Phosphorus-Loading Scenarios

Water-Resources Investigations Report 02–4181



Prepared in cooperation with the

Wisconsin Department of Natural Resources

USGS
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By Dale M. Robertson and Bernard N. Lenz

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Middleton, Wisconsin
2002

science for a changing world

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CONVERSION FACTORS AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To Obtain
meter (m)	3.2808	feet
square meters (m^2)	10.76391	square feet
kilometer (km)	.62137	miles
square kilometer (km^2)	247.105	acres
square kilometer (km^2)	.3861	square miles
cubic meters (m^3)	35.3147	cubic feet
cubic hectometer (hm^3)	3.51347×10^7	cubic feet
liter (L)	.26417	gallons
gram (g)	.0022	pounds
kilogram (kg)	2.2046	pounds
cubic meters per day (m^3/d)	.000409	cubic feet per second

Water year: Water year is defined as the period beginning October 1 and ending September 30, designated by the calendar year in which it ends.

Abbreviated water-quality units used in this report: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

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Response of the St. Croix River Pools, Wisconsin and Minnesota, to Various Phosphorus-Loading Scenarios

By Dale M. Robertson *and* Bernard N. Lenz

Abstract

The pools in the lower reach of the St. Croix National Scenic Riverway, Wisconsin and Minnesota, and the adjoining Lake Mallalieu, are eutrophic because of high phosphorus loading. To determine how changes in phosphorus loading would affect the trophic status of these pools, the water-quality model, BATHTUB, was used to simulate existing (1999) water quality and simulate the water quality with various phosphorus-loading scenarios. Water quality in the pools may respond differently during different flow regimes; therefore, sensitivity and scenario evaluations were performed not only for 1999, but also for a simulated period with relatively low flows throughout the basin (using flow data from 1988) and for a simulated period with relatively high flows throughout the basin (using flow data from 1996).

On the basis of the BATHTUB simulations, linear increases in phosphorus loading should cause the following changes in water quality in each of the pools: linear increases in phosphorus concentrations, although at a smaller rate than the increase in loading; non-linear increases in chlorophyll *a* concentrations, with a smaller relative response with higher phosphorus loading; increase in the frequency of algal blooms, with a higher frequency of intense algal blooms; and slightly decreased water clarity.

The response in water quality to changes in the phosphorus loading should be relatively similar regardless of the flow regime. Reducing phosphorus loading by about 50 percent would be necessary for the Lake St. Croix pools to be classified as mesotrophic with respect to phosphorus and chlorophyll *a* concentrations, whereas a larger reduction in phosphorus loading would be needed for Lake Mallalieu to be classified as mesotrophic. Even with these reductions, water clarity will remain poor because of the high non-algal turbidity and stained water in the pools.

INTRODUCTION

The St. Croix National Scenic Riverway (hereafter referred to as "Riverway") was established in 1968 as one of the original eight components of the National Wild and Scenic Rivers Act. The Riverway includes the St. Croix River from the Gordon Dam near Gordon, Wisconsin to the confluence with the Mississippi River at Prescott, Wisconsin, a distance of 247 km (fig. 1). The Riverway also includes the 158-km long Namekagon River from the Namekagon Dam near Cable, Wisconsin, to its confluence with the St. Croix River. Several pools are in the lower 100 km of the Riverway and include the St. Croix Falls Reservoir behind the hydropower dam at St. Croix Falls, and a series of natural pools downstream of Stillwater collectively called Lake St. Croix (fig. 2). The Willow River enters into the Lake St. Croix, near Hudson, Wisconsin. Lake Mallalieu is located behind the dam at the mouth of the Willow River (fig. 2). In this report, we refer to all of these pools as the "St. Croix River pools". Due to the proximity of this area to the Minneapolis/St. Paul, Minnesota, metropolitan area, it has experienced increased use and developmental pressure. Recreational use on the river has doubled since 1973 to nearly one million visitors per year (National Park Service, 1995).

In 1994, the National Park Service (NPS), Wisconsin Department of Natural Resources (WDNR), Minnesota Department of Natural Resources (MDNR), Metropolitan Council-Environmental Services (MCES), Minnesota Pollution Control Agency (MPCA), and Minnesota-Wisconsin Boundary Area Commission signed a Memorandum of Understanding that formed the interagency St. Croix Basin Water Resources Planning Team (hereafter referred to as

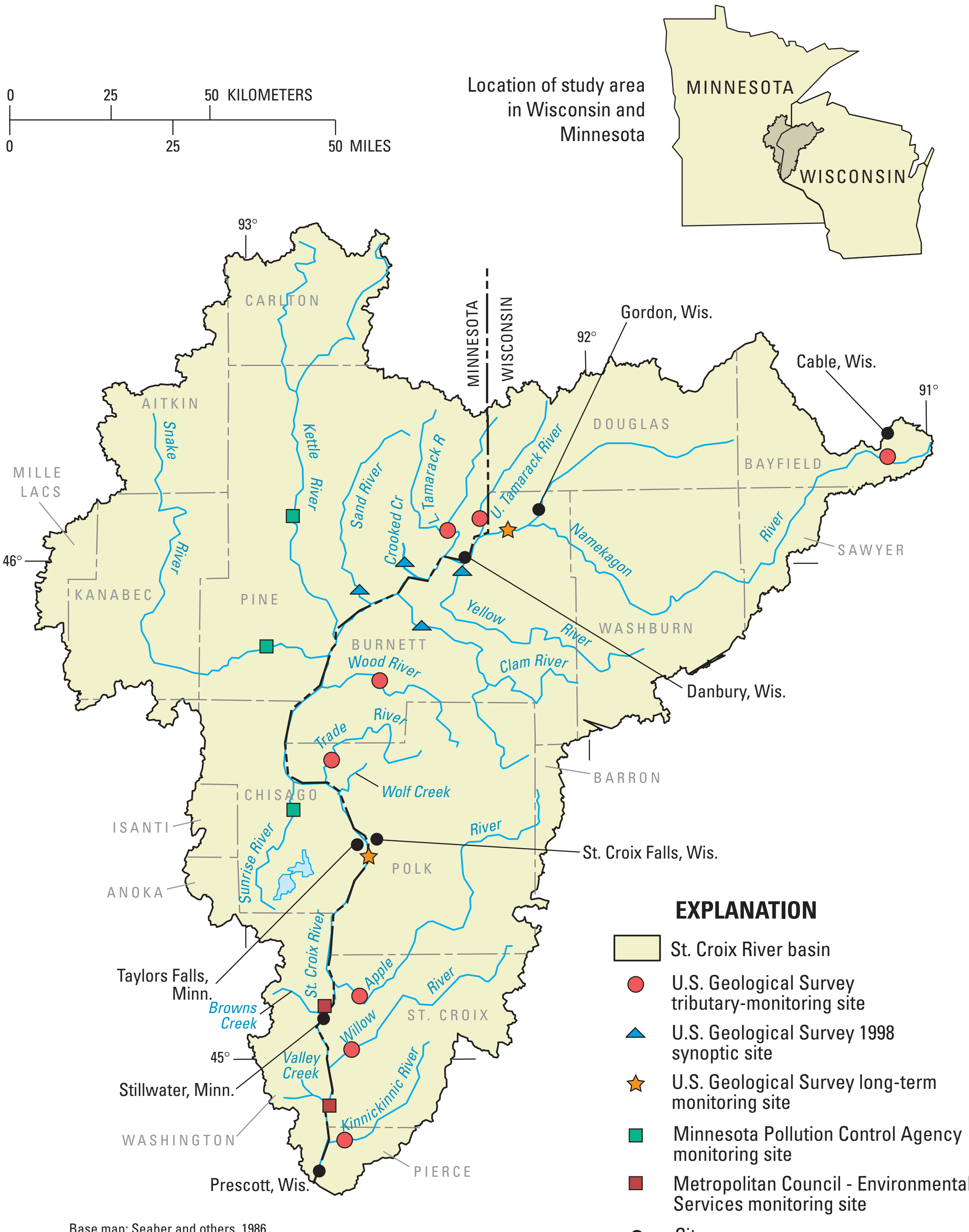


Figure 1. St. Croix River Basin, with stream sites sampled during 1997–99 identified.

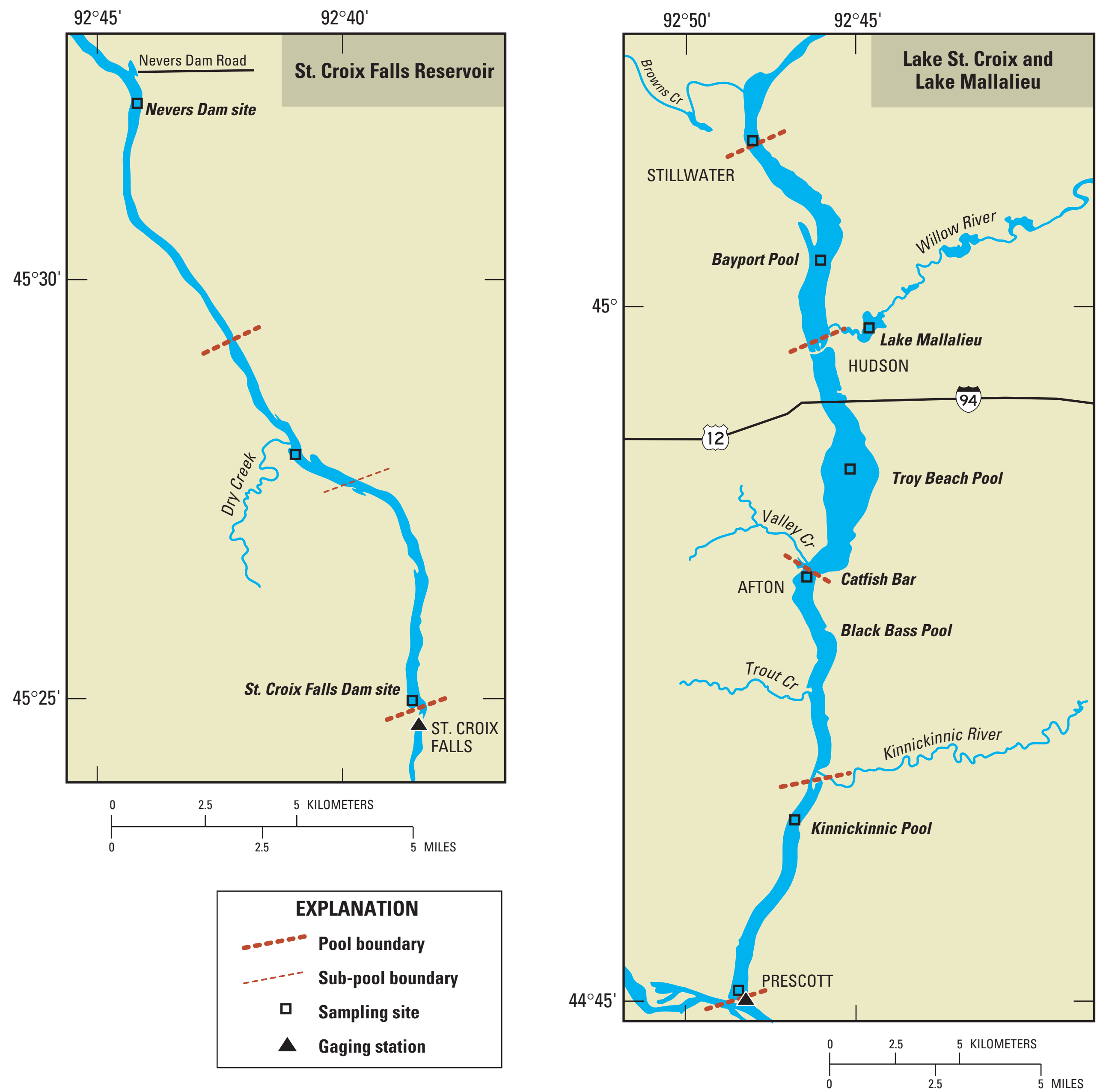


Figure 2. St. Croix River Pools, with pools and sampling locations identified.

"Basin Team") and agreed to investigate water-resource issues throughout the basin. Issues initially identified included effects from point and non-point sources of nutrient and suspended sediment loading, ground-water contamination, stormwater discharge, toxic contaminants, exotic species, impoundment, and recreational use.

The Basin Team developed a Water Resources Management Plan for the Riverway (Holmberg and others, 1997) that has been instrumental in securing funds for water-quality studies including an interagency nutrient and suspended sediment monitoring program with more than 25 sites monitored by six agencies during 1997–99 (Lenz and others, 2001). The Basin Team in collaboration with the U.S. Geological Survey (USGS) collected flow and water-quality data on the Riverway and its tributaries (fig. 1), especially in 1999. In this cooperative study between the USGS and the WDNR, we use the data collected from 1997–99 as part of other studies to calibrate and apply the water-quality model, BATHTUB (Walker, 1996), to the St. Croix River pools (fig. 2) to provide a better understanding of the sensitivity and anticipated trophic response of the system to changes in phosphorus loading from point and nonpoint sources. In future studies, the calibrated model can be used to evaluate the effects of specific management scenarios supplied by the Basin Team. This information will be used to update the Management Plan that will be used to help make nutrient-management decisions throughout the basin.

APPROACH

To determine the sensitivity of each of the St. Croix River pools to decreases and increases in phosphorus loading, the BATHTUB model was first calibrated using pool and tributary data collected in 1999 by the USGS, WDNR, MCES, MPCA, and NPS. The model was used to simulate the average water quality for the period from May 1 to September 30 rather than a full year because of the short water-residence time in each pool and this is when most vegetative growth occurs in most lakes in the area. Because of the distance between St. Croix Falls Reservoir and Lake St. Croix, and because several tributaries enter the St. Croix River downstream of St. Croix Falls, an attempt was made to develop two separate BATHTUB models—one model for St. Croix Falls Reservoir, and one for Lake Mallalieu/Lake St. Croix. An independent BATHTUB model was not developed for Lake Mallalieu because flow and water quality were not measured between Lake Mallalieu and Lake St. Croix.

Variability in rainfall intensity throughout the area in 1999 resulted in relatively high flows and loading from the northern part of the basin compared to that from the southern part (Lenz and others, 2001). Water quality in the various pools responds differently during different flow regimes. Therefore, sensitivity and scenario evaluations were performed not only for 1999, but also for a simulated period with relatively low flows throughout the basin (using flow data from 1988) and for a simulated period with relatively high flows throughout the basin (using flow data from 1996). During 1999, summer-average (May–September) flow at St. Croix Falls was exceeded in 31 of the past 99 years. In 1988, summer-average flow was exceeded in 92 of the past 99 years, and in 1996, summer-average flow was exceeded in 28 of the past 99 years. During each of these flow regimes, phosphorus loading from each tributary was estimated by use of flow-to-load relations based on 1997–99 data, and loading from other sources was assumed to be similar to that estimated for 1999.

METHODS

Loads and Concentrations

Seasonal loads of total and dissolved ortho-phosphorus from most monitored tributaries were estimated with a regression approach by use of the Estimator program (Cohn and others, 1989). Estimated daily loads (L) were computed on the basis of relations determined between constituent load (in kilograms) and two variables: flow (Q, in cubic meters per day) and time of the year (T, in radians). The general form of the model was

$$\log (L) = a + b\,[\log (Q) - c] + d\,[\log (Q) - c]^2 + e\,[\sin (T)] + f\,[\cos (T)] \qquad (1)$$

Values for the regression coefficients (*a, b, c, d, e,* and *f*) in Equation 1 were computed for each site by the use of a multiple regression analysis between daily loads (daily average flows multiplied by instantaneous measured concentrations), daily flows (Q), and time of the year (T). The flow-to-load relation in Equation 1 was calibrated for each site using all available data from 1997–99 in the regression analysis. Only those terms that were significant at $p < 0.05$ were included in the regression. Because a logarithmic transformation was used in Equation 1, estimated daily loads were adjusted to account for a re-transformation bias by use of the minimum variance unbiased estimate (MVUE) procedure (see Cohn and others, 1989, for a complete discussion).

The flow-to-load relations developed by use of Equation 1 and the daily flow data from 1999 were used to compute tributary loads of total and dissolved ortho-phosphorus for May through September for all monitored tributaries, except Browns and Valley Creeks. Total phosphorus loads for Browns and Valley Creeks for 1999 were computed by the MCES with the use of the model FLUX (Walker, 1996).

Tributary loading for the simulated low- and high-flow regimes were calculated by use of the same flow-to-load relations (developed by use of Eq. 1) with the actual or estimated flows for 1988 (low-flow regime) and 1996 (high-flow regime). Actual flows for these years from the St. Croix River (at St. Croix Falls) and Apple River were used. Flows for these years were not available for the Willow and Kinnickinnic Rivers and, therefore, were estimated by adding or removing high flows (peaks) in the 1999 daily flow records for those sites. All significant peaks in flow were removed for the low-flow estimates, while for the high-flow estimates, event peaks were added on the basis of the relative increases in flow at nearby sites with actual continuous or peak-flow data, the magnitude of known peaks that have occurred at the site in the past, the percent increase over 1999 flows in the actual Apple River and St. Croix River flow records, and professional judgment. Baseflow during the low-flow and high-flow regimes was assumed to be similar to that in 1999. Because the flow-to-load relations were based only on available 1997–99 water-quality data, the estimated loads during the simulated low- and high-flow regimes may differ from those from 1988 and 1996.

Flow-to-load relations were not available for Browns and Valley Creeks; therefore, the percent changes in the flow and phosphorus concentrations in the Apple River between the simulated wet and dry years and those measured for 1999 were used to adjust the phosphorus loading for these two sites. In other words, similar percent changes in flow and concentration were assumed to take place in Browns and Valley Creeks as those measured in the Apple River.

Volumetrically weighted mean concentrations of total and dissolved ortho-phosphorus for May through September were then computed by dividing the total load by the total flow during this period. In tributaries where total phosphorus concentrations were measured but dissolved ortho-phosphorus concentrations were not, volumetrically weighted mean concentrations of dissolved ortho-phosphorus were set to be one-third of the total phosphorus concentration, which is approximately the fraction observed in most other monitored tributaries.

Volumetrically weighted mean chloride concentrations were computed for May through September, 1999, in a similar manner to that for total phosphorus. Average total and inorganic nitrogen concentrations for 1999 were computed by averaging the concentrations measured in each tributary from May through September, 1999. The concentrations measured for total and inorganic nitrogen in 1999 were also used for dry- and wet-year simulations. In other words, no adjustments in nitrogen concentrations were made for the various flow regimes.

Confidence Limits and Errors

The coefficient of variation was computed for each of the inputs to BATHTUB (water-quality concentrations and flow estimates). These values were used within BATHTUB to calculate an estimate of the certainty (plus and minus one standard error of the estimate) for each simulated value.

PHYSICAL AND CHEMICAL CHARACTERISTICS (MODEL INPUTS)

Three types of data are required as input to the BATHTUB model: morphometric information for each pool or basin in the model, water-quality data for each pool, and nutrient loading to each pool from all sources. The water-quality and nutrient-loading data were averaged over the period from May 1 through September 30, 1999. This period was chosen rather than a full year because of the short water residence time in each pool and because May through September represents the period when most vegetative growth occurs in most lakes in the area.

Basin Morphometry and Water Level

The surface area and volume of each of the pools, as delineated in figure 2, are based on an average water level during May–September, 1999 (table 1). The aver-

Table 1. Morphometry of each of the St. Croix River pools based on an average water level during May–September, 1999, and mean depths during 1999, the simulated dry year (1988), and the simulated wet year (1996)

[km, kilometers, km^2, square kilometers; m^3, cubic meters, m, meters; --, not determined]

Pool name	Average 1999 water level			Mean depth (m)		
	Length (km)	Area (km^2)	Volume (m^3 x10^6)	1999	Dry year (1988)	Wet year (1996)
St. Croix Falls Reservoir	10.1	2.414[a]	9.6	4.0[b]	--	--
Lake Mallalieu	2.4	1.093	1.8	1.6	1.6	1.6
Bayport Pool	9.7	11.340	77.1	6.8	6.2	7.3
Troy Beach Pool	9.7	12.660	133.0	10.5	9.9	11.0
Black Bass Pool	11.3	5.450	73.6	13.5	12.9	14.0
Kinnickinnic Pool	8.1	5.830	57.1	9.8	9.2	10.3

[a]Area computed based on the mean width being assumed to be similar to that from St. Croix Falls Dam to the sub-pool boundary (fig. 2).

[b]Mean depth assumed to be similar to that from St. Croix Falls Dam to sub-pool boundary (fig. 2).

age water level during the simulation period (May 1 through September 30) for each of the St. Croix River pools was estimated for each of the three flow regimes from water levels measured at Prescott and Stillwater during 1988, 1996, and 1999 (the average water level of St. Croix Falls Reservoir was only estimated for 1999). Water levels in the simulated dry year (1988) were 0.6 m lower than in 1999. Water levels during the simulated wet year (1996) were 0.5 m higher than in 1999. The mean depth of each pool for each flow regime (table 1) was computed by adding or subtracting the average change in water level. The water level in Lake Mallalieu is maintained at a near constant water level; therefore, its mean water depth was kept constant at 1.6 m in all simulations.

Water Quality in the St. Croix River Pools

Water-quality data for each of the St. Croix River pools (sampling sites are shown in fig. 2) were collected from May through September, 1999. Water-quality data were collected bi-weekly at three locations in and above the St. Croix Falls Reservoir (by the NPS), one location in Lake Mallalieu (by the WDNR), and eight locations in Lake St. Croix (water quality by the MCES and WDNR, and Secchi depths by volunteers-only sites for which data were used are identified in fig. 2). Water-quality data were not measured in the Black Bass Pool; therefore, the water-quality data for this pool were calculated by averaging data collected at Catfish Bar (just upstream) and in the Kinnickinnic Pool (just downstream). These data were summarized into mean monthly and seasonal (May–September) concentrations. The average summer data are given in table 2.

Water quality was relatively uniform throughout the St. Croix Falls Reservoir. The quality of the water within the reservoir was similar to that which entered and exited the reservoir (fig. 3). Nutrient concentrations were high; the average total phosphorus concentration was almost 100 µg/L, and average total nitrogen concentration was about 1,000 µg/L. The average dissolved ortho-phosphorus concentration was about 20 µg/L. Chlorophyll *a* concentrations, however, were relatively low and averaged only about 13 µg/L. The average Secchi depth was about 1 m.

The ratio of near-surface concentrations of total nitrogen to total phosphorus is often used to determine the potential limiting nutrient in a lake. The specific value of when this ratio determines which nutrient is potentially limiting, however, varies under different conditions (Correll, 1998). Therefore, a range in the ratio is often used to determine the potential limiting nutrient. A ratio greater than about 15:1, by weight, indicates that phosphorus is potentially the limiting nutrient, whereas a ratio less than 5:1, by weight, indi-

Table 2. Average summer (May–September) water quality for various locations (identified in fig. 2) in the St. Croix River pools, 1999

[N, nitrogen; P, phosphorus; Chl *a*, chlorophyll *a*; Cl, chloride; TSS, total suspended sediment; µg/L, micrograms per liter; m, meters; cv, coefficient of variation; --, not measured; data within St. Croix Falls Reservoir were collected by the National Park Service, within Lake Mallalieu and the Bayport, Troy Beach, Catfish Bar, and Kinnickinnic Pools by the Wisconsin Department of Natural Resources, at Stillwater and Prescott by the Metropolitan Council-Environmental Services, and Secchi depth data in Lake St. Croix by volunteers; data for Black Bass Pool were computed as the average of concentrations measured at Catfish Bar and in the Kinnickinnic Pool]

		Total N (µg/L)	Total P (µg/L)	Ortho-P [µg/L)	N : P ratio	Chl *a* (µg/L)	Secchi (m)	Cl (µg/L)	TSS (µg/L)
St. Croix Falls Reservoir									
Nevers Dam Road		996	100	18	10.0	11	1.0	2,900	9,100
	cv	0.14	0.75	0.23	--	0.44	0.21	0.38	0.31
Dry Creek		859	96	17	8.9	14	1.1	2,900	8,500
	cv	.34	.73	.37	--	.24	.17	.25	.33
St. Croix Falls		875	84	17	10.4	13	1.0	2,900	7,270
	cv	.24	.59	.30	--	.28	.25	.25	.30
Lake Mallalieu									
Lake Mallalieu		2,262	111	14	20.4	79	.7	11,530	19,600
	cv	.13	.50	1.01	--	.35	.26	.08	.51
Lake St. Croix									
Stillwater		908	72	17	12.6	19	--	4,000	8,800
	cv	.11	1.03	.32	--	.34		.39	.22
Bayport		1,027	52	14	19.6	15	1.2	4,520	4,780
	cv	.12	.18	.50	--	.55	.21	.11	.29
Hudson		1,041	52	16	20.2	12	1.8	7,580	4,720
	cv	.15	.22	.58	--	.64	1.19	1.27	.43
Troy Beach		1,161	50	15	23.1	9	1.4	4,790	3,740
	cv	.08	.19	.63	--	.91	.31	.10	.40
Catfish Bar		1,183	47	23	25.2	9	1.6	6,380	3,020
	cv	.24	.19	.77	--	1.06	.23	.60	.31
Black Bass		1,215	45	20	26.8	8	1.6	6,165	3,365
	cv	.18	.21	.71	--	1.10	.23	.46	.37
Kinnickinnic		1,247	44	18	28.5	8	--	5,950	3,710
	cv	.12	.23	.65	--	1.15	--	.33	.43
Prescott		1,188	50	16	23.8	17	--	4,200	4,500
	cv	.26	.74	.73	--	1.22	--	.22	.40

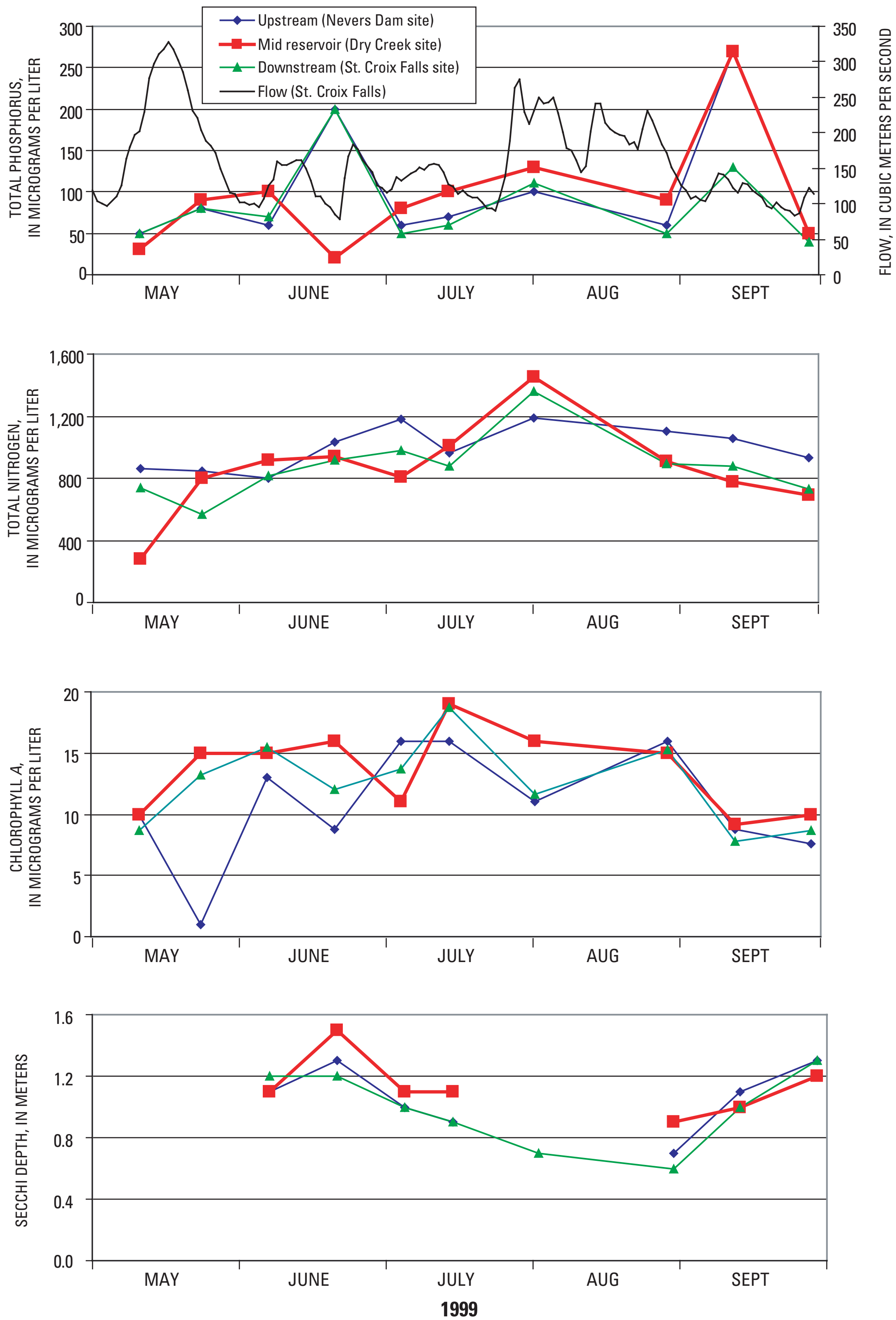


Figure 3. Water quality at three locations in St. Croix Falls Reservoir (upstream of reservoir near Nevers Dam Road, mid reservoir near Dry Creek, and downstream end of reservoir at St. Croix Falls) from May through September, 1999, and streamflow at St. Croix Falls, Wis.

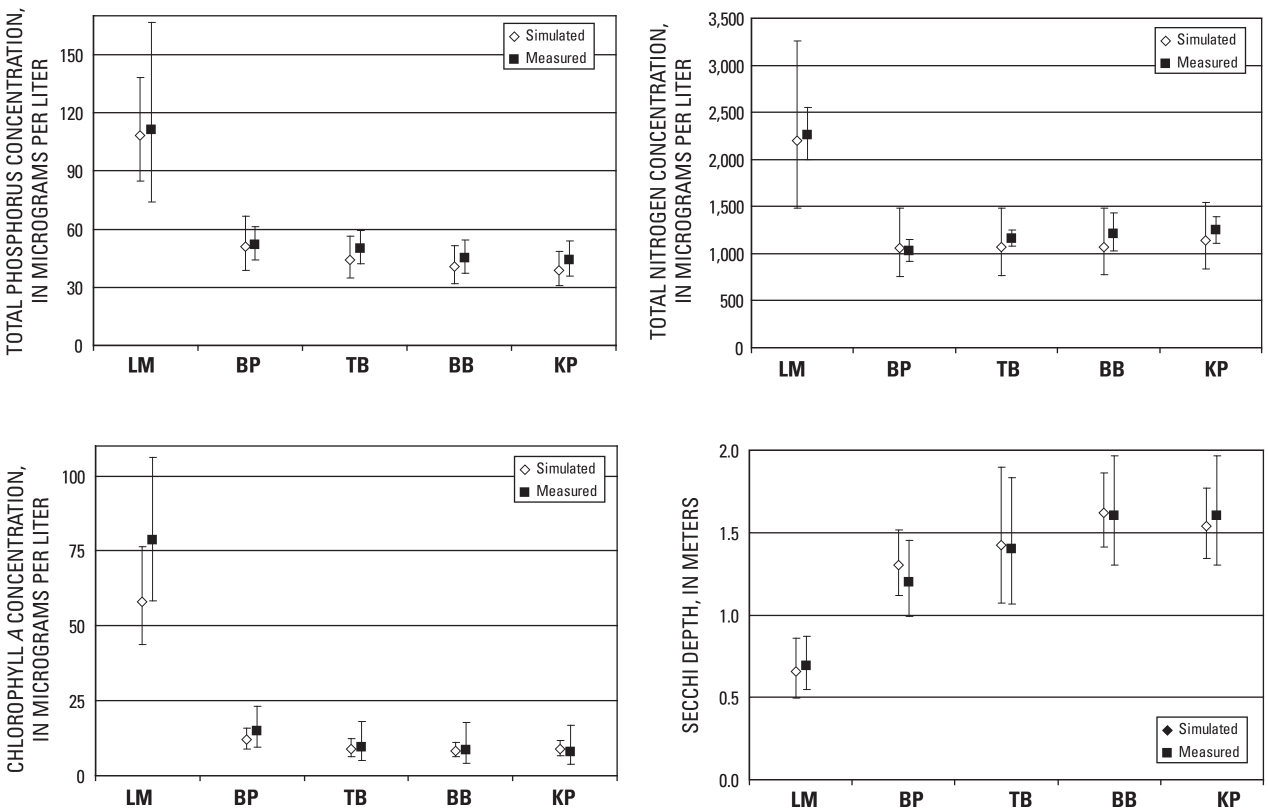


Figure 4. Measured and simulated (from BATHTUB) water quality in Lake Mallalieu and Lake St. Croix pools (summer average, May–September, 1999). Vertical lines on each data point represent plus and minus one standard error in the values [LM, Lake Mallalieu; BP, Bayport Pool; TB, Troy Beach Pool; BB, Black Bass Pool; KP, Kinnickinnic Pool].

cates that nitrogen should be the limiting nutrient. A value between these two ratios indicates the two nutrients can be co-limiting. The average nitrogen-to-phosphorus ratio for the St. Croix Falls Reservoir was about 10:1 (table 2); therefore, nitrogen and phosphorus can both limit potential algal growth.

Variations in water quality throughout Lake Mallalieu and Lake St. Croix are shown in figure 4. In Lake Mallalieu, average summer nutrient and chlorophyll *a* concentrations were very high (concentrations of total phosphorus and chlorophyll *a* were 111 µg/L and 79 µg/L, respectively) and Secchi depths were low (average depth of 0.7 m) compared to Lake St. Croix, which had average total phosphorus concentrations of 45 to 52 µg/L and chlorophyll *a* concentrations of 8 to 15 µg/L. Dissolved ortho-phosphorus concentrations ranged from 14 to 23 µg/L, with no consistent trend throughout the system. Phosphorus and chlorophyll *a* concentrations decreased slightly from the Bayport Pool (upstream) to the Kinnickinnic Pool (downstream), whereas water clarity (Secchi depth) improved slightly from the Bayport Pool (1.2 m) to the Kinnickinnic Pool (1.6m).

The average nitrogen-to-phosphorus ratio in Lake Mallalieu and each of the pools of Lake St. Croix was about 20:1 (table 2). This ratio dropped below 10:1 only once in Lake Mallalieu during 1999 and was never measured less than 17:1 in any Lake St. Croix pool. Therefore, if just nitrogen and phosphorus are considered, phosphorus is the nutrient in shortest supply and will almost always be the nutrient limiting algal growth in these pools.

Table 3. Tributary phosphorus loading (May–September) to lower St. Croix River pools
[Names in parentheses are the streams used for extrapolation to unmonitored areas; kg, kilograms; monitored, monitored area during 1999]

Tributary	1999		Simulated dry year		Simulated wet year	
	kg	Percent	kg	Percent	kg	Percent
Willow River monitored	4,485	3.8	2,952	8.7	5,910	4.0
Lake Mallalieu unmonitored (Willow)	123	.1	81	.2	162	.1
St. Croix River monitored	85,059	71.5	18,472	54.7	101,802	69.3
St. Croix River unmonitored	2,579	2.2	560	1.7	3,087	2.1
Apple River monitored	11,595	9.7	2,776	8.2	14,738	10.0
Apple River unmonitored	621	.5	149	.4	789	0.5
Browns Creek monitored	1,508	1.3	316	.9	1,916	1.3
Valley Creek monitored	451	.4	108	.3	573	.4
Troy Beach Pool unmonitored (Apple)	2,945	2.5	705	2.1	3,742	2.5
Black Bass Pool unmonitored (Willow)	292	.2	192	.6	385	.3
Kinnickinnic River monitored	3,275	2.8	1,841	5.4	6,850	4.7
Kinnickinnic Pool unmonitored (Kinnickinnic)	913	.8	513	1.5	1,910	1.3
Total Tributary Load	113,845	100.0	28,667	100.0	141,862	100.0

Sources of Nutrients to the St. Croix River Pools

Tributaries

Daily average flow data for May through September for 1999, a simulated dry year (using flows measured in 1988), and a simulated wet year (using flows measured in 1996) were input into the flow-to-load relations (developed based on 1997–99 data) for each monitored tributary to calculate daily loads for total and dissolved ortho-phosphorus from all monitored tributaries to the St. Croix River pools (table 3). Loads from selected tributaries were then used to estimate the loading from unmonitored areas by use of drainage-area ratios with monitored streams. The stream used to estimate loading from each unmonitored area is given in parentheses in table 3. Loads from most unmonitored areas were extrapolated from the nearest monitored stream, except for tributaries to the Troy Beach Pool and the Black Bass Pool. Unmonitored areas of the Bayport Pool were extrapolated from the St. Croix River at St. Croix Falls and the Apple River. Unmonitored areas of Lake Mallalieu and the Black Bass Pool were extrapolated from the Willow River. Unmonitored areas of the Troy Beach Pool were extrapolated from the Apple River. These sites were chosen because their watersheds had similar land use as the unmonitored areas.

Volumetrically weighted mean concentrations for total and dissolved ortho-phosphorus were computed by dividing the sum of the daily loads by the sum of the daily flows for May–September. Flows and mean concentrations for total and dissolved ortho-phosphorus for 1999 are listed in table 4 (along with concentrations for the nitrogen species and chloride). Concentrations based on flows for the simulated dry year (flows from 1988) and simulated wet year (flows from 1996) are listed in table 5. Average flow and volumetrically weighted mean concentrations for the unmonitored areas were extrapolated in a similar manner to that described for loads. The tributaries used for each unmonitored area are given in tables 4 and 5.

Point Sources

Contributions of nutrients from point sources that discharge directly into the St. Croix River pools (direct point sources) and from point sources that discharge into the tributaries and incorporated into the loads in table 3 (indirect point sources) were determined for May–September, 1999. Contributions from each point source were computed based on water-quality and flow

Table 4. Total flow and volumetrically weighted mean water quality for monitored and unmonitored areas of the study area for May–September 1999

[Names in parentheses are the streams used for extrapolation to unmonitored areas; P, phosphorus; N, nitrogen; km^2, square kilometers; hm^3, cubic hectometers (millions of cubic meters); µg/L, micrograms per liter; cv, coefficient of variation; monitored, monitored area in 1999; WWTP, wastewater treatment plant; POTW, publicly owned treatment works; --, not applicable; chloride concentrations from WWTPs and hatcheries were assumed to be 50,000 and 4,000 µg/L, respectively; cv for point sources assumed to be 0.25]

	Area	Flow		Total P		Ortho-P		Total N		Inorganic N		Chloride	
Tributary	km^2	hm^3	cv	µg/L	cv	µg/L	cv	µg/L	cv	µg/L	cv	µg/L	cv
Willow River monitored	756.0	52.37	0.04	86	0.45	29	0.46	2,203	0.50	1,490	0.50	12,191	0.45
Lake Mallalieu unmonitored (Willow)	20.7	1.44	.04	86	.45	29	.46	2,203	.50	1,490	.50	12,191	.45
St. Croix River monitored	16,162.0	2,079.17	.06	41	.51	13	.48	971	.50	157	.50	4,410	.47
St. Croix River unmonitored	490.0	63.04	.06	41	.51	13	.48	971	.50	157	.50	4,410	.47
Apple River monitored	1,500.0	180.33	.05	64	.48	18	.46	1,332	.50	802	.50	7,492	.49
Apple River unmonitored	80.3	9.66	.05	64	.48	18	.46	1,332	.50	802	.50	7,492	.49
Browns Creek monitored	79.8	6.34	.09	238	.45	79	.50	2,203	.50	1,490	.50	12,191	.45
Valley Creek monitored	33.7	5.58	.04	81	.50	27	.50	2,203	.50	1,490	.50	12,191	.50
Troy Beach Pool unmonitored (Apple)	380.7	45.80	.05	64	.48	18	.46	1,332	.50	802	.50	7,492	.49
Black Bass Pool unmonitored (Willow)	49.2	3.41	.04	86	.45	29	.46	2,203	.50	1,490	.50	12,191	.45
Kinnickinnic River monitored	427.4	38.21	.02	86	.45	60	.45	4,767	.50	4,447	.50	16,612	.45
Kinnickinnic Pool unmonitored (Kinnickinnic)	119.1	10.65	.02	86	.45	60	.45	4,767	.50	4,447	.50	16,612	.45
Osceola Hatchery	--	1.10	.00	70	.25	70	.25	2,202	.25	1,900	.25	4,000	.25
Osceola WWTP	--	.17	.01	4,696	.25	4,604	.25	14,237	.25	10,517	.25	50,000	.25
St. Croix Falls Hatchery	--	1.74	.20	117	.25	83	.25	2,438	.25	2,038	.25	4,000	.25
St. Croix Falls POTW	--	.16	.02	3,418	.25	2,760	.25	13,981	.25	11,193	.25	50,000	.25
Stillwater POTW	--	2.04	.01	341	.25	307	.25	17,900	.25	13,900	.25	50,000	.25
Taylor POTW	--	.07	.36	2,162	.25	1,946	.25	17,900	.25	13,900	.25	50,000	.25
Hudson WWTP	--	.66	.01	3,953	.25	3,486	.25	25,351	.25	20,080	.25	50,000	.25
Amani POTW	--	.01	.24	2,001	.25	2,001	.25	17,900	.25	13,900	.25	50,000	.25

Table 5. Total flow and volumetrically weighted mean water quality for monitored and unmonitored areas of the study area for May–September for the simulated dry year (based on 1988 flow data) and simulated wet year (based on 1996 flow data)

[Names in parentheses are the streams used for extrapolation to unmonitored areas; P, phosphorus; N, nitrogen; hm^3, cubic hectometers (millions of cubic meters); µg/L, micrograms per liter; cv, coefficient of variation; monitored, monitored area in 1999; WWTP, wastewater treatment plant; POTW, publicly owned treatment works]

Tributary	Simulated dry year						Simulated wet year					
	Total Flow		Total P		Ortho-P		Total Flow		Total P		Ortho-P	
	hm^3	cv	µg/L	cv	µg/L	cv	hm^3	cv	µg/L	cv	µg/L	cv
Willow River monitored	39.3	0.02	75	0.45	24	0.45	63.2	0.06	94	0.49	34	0.51
Lake Mallalieu unmonitored (Willow)	1.1	.02	75	.45	24	.45	1.7	.06	94	.49	34	.51
St. Croix River monitored	838.6	.10	22	.56	11	.47	2,154.8	.10	47	.62	14	.56
St. Croix River unmonitored	25.4	.10	22	.56	11	.47	65.3	.10	47	.62	14	.56
Apple River monitored	65.7	.06	42	.45	21	.45	205.7	.09	72	.56	18	.51
Apple River unmonitored	3.5	.06	42	.45	21	.45	11.0	.09	72	.56	18	.51
Browns Creek monitored	2.0	.09	156	.45	89	.50	7.2	.09	265	.56	76	.50
Valley Creek monitored	2.0	.06	53	.45	30	.50	6.4	.09	90	.56	26	.50
Troy Beach Pool unmonitored (Apple)	16.7	.04	42	.45	21	.45	52.2	.04	72	.56	18	.51
Black Bass Pool unmonitored (Willow)	2.6	.02	75	.45	24	.45	4.1	.06	94	.49	34	.51
Kinnickinnic River monitored	29.2	.02	63	.45	48	.45	48.6	.05	141	.51	85	.49
Kinnickinnic Pool unmonitored (Kinnickinnic)	8.1	.02	63	.45	48	.45	13.5	.05	141	.51	85	.49
Osceola Hatchery	1.1	.00	70	.25	70	.25	1.1	.00	70	.25	70	.25
Osceola WWTP	.2	.01	4,696	.25	4,604	.25	.2	.01	4,696	.25	4,604	.25
St. Croix Falls Hatchery	1.7	.20	117	.25	83	.25	1.7	.20	117	.25	83	.25
St. Croix Falls POTW	.2	.02	3,418	.25	2,760	.25	.2	.02	3,418	.25	2,760	.25
Stillwater POTW	2.0	.01	341	.25	307	.25	2.0	.01	341	.25	307	.25
Taylor POTW	.1	.36	2,162	.25	1,946	.25	.1	.36	2,162	.25	1,946	.25
Hudson WWTP	.7	.01	3,953	.25	3,486	.25	.7	.01	3,953	.25	3,486	.25
Amani POTW	.0	.24	2,001	.25	2,001	.25	.0	.24	2,001	.25	2,001	.25

data obtained from the WDNR, MCES, and MPCA. The total load of phosphorus from direct point sources was 5,125 kg (table 6). The total input from indirect point sources within the tributary basins was about 7,000 kg. Point-source loads are generally stable from year to year; therefore, 1999 direct point-source loads were applied unchanged to the simulated dry and wet years. Mean concentrations for total and dissolved ortho-phosphorus for the direct point sources were computed by dividing the seasonal load by the total seasonal flow from May–September (tables 4 and 5).

Table 6. Phosphorus loading to St. Croix River pools from point sources, May–September 1999

[WWTP, wastewater treatment plant; POTW, publicly owned treatment works]

Source	Kilograms
Direct point sources to lower pools	
St. Croix Falls Hatchery	204
St. Croix Falls POTW	540
Osceola Hatchery	77
Osceola WWTP	812
Stillwater POTW	697
Taylor POTW	160
Hudson WWTP	2,621
Amani POTW	14
Total	**5,125**
Indirect point sources in tributary basin	
Basin	**Kilograms**
Yellow River	81
Clam River	477
Kettle River	98
Snake River	852
Wood River	437
Apple River	859
Willow River	1,374
Kinnickinnic River	2,760
Total	**6,938**

Atmospheric Sources

The total precipitation to the pools was obtained by averaging that measured at Baldwin, Wis., and River Falls, Wis. from May–September, 1999. Atmospheric input of phosphorus to the surface of each pool (table 7) was estimated by multiplying a typical atmospheric deposition rate of phosphorus (30 kg/km^2 per year; Walker, 1996) by the surface area of each pool (table 1) and the fraction of year during the simulation period (0.417). The total estimated input of phosphorus from precipitation was 455 kg.

Sediment Release

Phosphorus release rates from the sediments was previously estimated at four locations in Lake St. Croix by William James (U.S. Army Corps of Engineers, Eau Galle Aquatic Ecology Laboratory, written commun., 1999; table 8). Dissolved oxygen concentrations measured in the pools demonstrated only limited periods of anoxia. Therefore, based on the release rates in table 8 and the calibration process for the BATHTUB model, the internal sediment release rates were set to 5 mg/m^2/day in Lake Mallalieu, 2 mg/m^2/day in the Bayport Pool, and 1 mg/m^2/day in the Troy Beach, Black Bass, and Kinnickinnic Pools. Based on these rates, the total internal sediment release was about 8,000 kg (table 7). Sediment release rates were not adjusted for wet and dry years.

Summary of Phosphorus Inputs

For all flow regimes, tributary input was the major source of phosphorus to the Lake Mallalieu/Lake St. Croix pools (ranging from about 68 percent of the total in the simulated dry year to about 91 percent in the simulated wet year, table 9 and fig. 5). Point sources that discharge directly into the pools represent about 3 to 4 percent of the total phosphorus loading in 1999 and the simulated wet year, and about 12 percent of the total loading in the simulated dry year. However, part of the total estimated tributary load is actually from other indirect point sources in the tributary basins and incorporated into the tributary estimates in table 3. If it is assumed that all tributary point sources reached the pools–an extreme assumption–all point sources of phosphorus would contribute 9.4 percent (4 percent from direct input and 5.4 percent from indirect point sources, table 9) of the total phosphorus load in 1999, 28.7 percent of the total in the simulated dry year, and 7.8 percent in the simulated wet year. Atmospheric input of phosphorus contributed only 0.4 to 1.1 percent of the total input. Input from sediment release is estimated to range from about 5 percent of the total input in 1999 and other wet years to about 19 percent in dry years.

Table 7. Phosphorus loading from atmospheric inputs and sediment release into Lake Mallalieu and Lake St. Croix, during May–September

Pool	Atmospheric input kilograms	Sediment release kilograms
Lake Mallalieu	14	832
Bayport Pool	142	3,452
Troy Beach Pool	158	1,927
Black Bass Pool	68	829
Kinnickinnic Pool	73	887
Total	**455**	**7,927**

Table 8. Phosphorus release rates from the sediments of Lake St. Croix, by W. James (U.S. Army Corps of Engineers, Eau Galle Aquatic Ecology Laboratory, written commun., 1999)

[mg/m^2/d, milligrams per square meter per day]

Station	Oxic conditions mg/m^2/d	Anoxic conditions mg/m^2/d
Bayport Pool - Site 1	0.7	26.1
Bayport Pool - Site 2	.7	17.8
Troy Beach Pool - Site 1	.3	8.6
Troy Beach Pool - Site 2	.2	10.9

Table 9. Summary of phosphorus loading to Lake Mallalieu/Lake St. Croix pools

Source	1999		Dry year (1988)		Wet year (1996)	
	Kilograms	Percent	Kilograms	Percent	Kilograms	Percent
Total tributary load	113,845	89.4	28,667	68.0	141,862	91.3
Point sources in basins	6,938	5.4	6,938	16.5	6,938	4.5
Direct point sources	5,125	4.0	5,125	12.2	5,125	3.3
Atmospheric input	455	.4	455	1.1	455	.3
Sediment input	7,927	6.2	7,927	18.8	7,927	5.1
Total phosphorus input	127,352	100.0	42,173	100.0	155,369	100.0

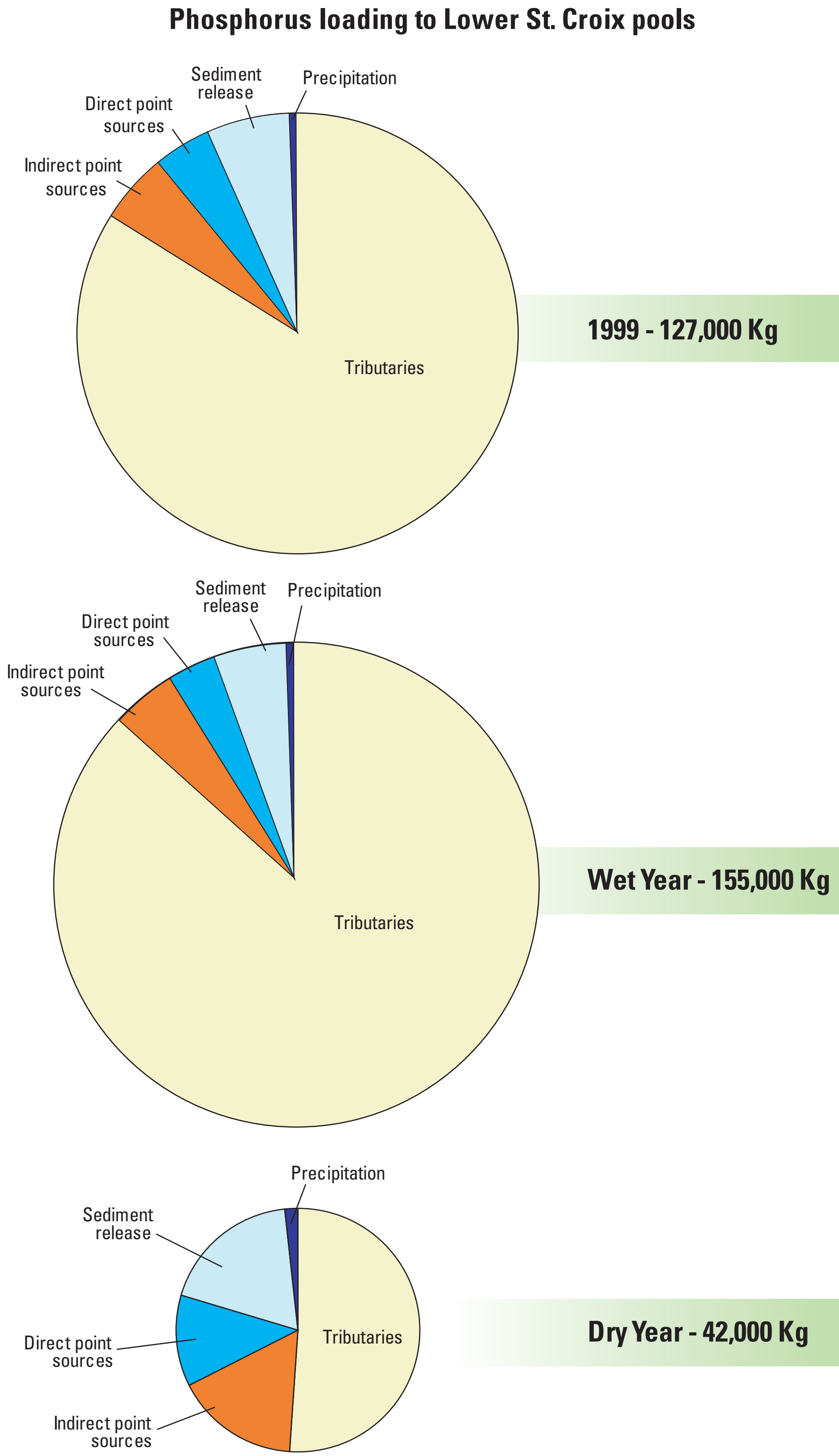


Figure 5. Phosphorus loading to lower St. Croix River pools (Lake Mallalieu and Lake St. Croix pools) for the 1999 flow regime, simulated dry year (flows based on 1988 data), and simulated wet year (flows base on 1996 data).

Water-Residence Time

Flow data from May–September, 1999, and the simulated dry and wet years were used to determine the average water-residence time in each St. Croix River pool (table 10). In 1999 and the simulated wet year, the average water-residence time in each pool was very short, ranging from 0.4 days to 8.2 days. During these years, St. Croix Falls Reservoir had an average water-residence time of 0.4 days, which explains the similarity in the quality of the water entering, within, and exiting the reservoir. In Lake Mallalieu, the average water-residence time was 5 days. The average water-residence times in the Lake St. Croix pools ranged from 3.4 days in the Kinnickinnic Pool to 8.2 days in the Troy Beach Pool, and for all four pools of Lake St. Croix, combined, was 21 days.

Table 10. Water-residence time in the St. Croix River pools

Pool	Average water-residence time (days)		
	1999	Dry year	Wet year
St. Croix Falls Reservoir	0.4	0.9	0.4
Lake Mallalieu	5.0	6.7	4.1
Bayport Pool	4.9	11.0	5.0
Troy Beach Pool	8.2	19.4	8.1
Black Bass Pool	4.5	11.0	4.3
Kinnickinnic Pool	3.4	8.1	3.3
Lake St. Croix (four pools combined)	20.6	50.1	20.0

In the simulated dry year, the average water-residence time was about twice that of 1999, except in Lake Mallalieu where it was only slightly longer (6.7 days). During the simulated dry year, the average water-residence time for the Lake St. Croix pools ranged from 8.1 days in the Kinnickinnic Pool to 19.4 days in the Troy Beach Pool, and for all four pools of Lake St. Croix, combined, was 50.1 days.

RESPONSE IN THE WATER QUALITY OF ST. CROIX FALLS RESERVOIR TO CHANGES IN PHOSPHORUS LOADING

An attempt was made to develop a BATHTUB model for the St. Croix Falls Reservoir; however, because the average water-retention time in the reservoir was less than one day (table 10), the empirical models within BATHTUB did not work well in simulating its water quality. Because of this short water-retention time, the quality of the water entering the reservoir was similar to that exiting except during a few occasions (fig. 3). These exceptions appear to be due primarily to errors in the data set.

Because the short water-retention time and the similarity of the quality of water entering and exiting the reservoir, a detailed reservoir model is not needed to simulate the water-quality response to various loading scenarios. The change in phosphorus concentrations in the reservoir should be of similar magnitude to the change in phosphorus loading. For example, if phosphorus loading is reduced by 50 percent, the phosphorus concentration in the reservoir should also decrease by about 50 percent. Chlorophyll *a* concentrations and Secchi depths also vary very little throughout the reservoir (fig. 3), but their response may not be of similar magnitude to the change in loading. Therefore, a river model is needed to estimate the changes that should occur in chlorophyll *a* concentrations and Secchi depths upstream and within St. Croix Falls Reservoir in response to changes in phosphorus loading.

MODELING THE RESPONSE IN WATER QUALITY OF LAKE MALLALIEU AND LAKE ST. CROIX TO CHANGES IN PHOSPHORUS LOADING

Because of the longer water retention time in Lake Mallalieu and Lake St. Croix than in St. Croix Falls Reservoir, the water quality within these pools differs from the water entering them. Therefore, the empirical models within BATHTUB are applicable to describe the changes in the water quality in these pools.

Hydrology

To determine the calibration factors within BATHTUB for dispersion or exchange of water between adjacent pools, the volumetrically weighted mean chloride concentrations for 1999 for each tributary were input into the model, and estimated and measured chloride concentrations were compared for each pool (fig. 6). An estimate of the certainty of the measured and estimated

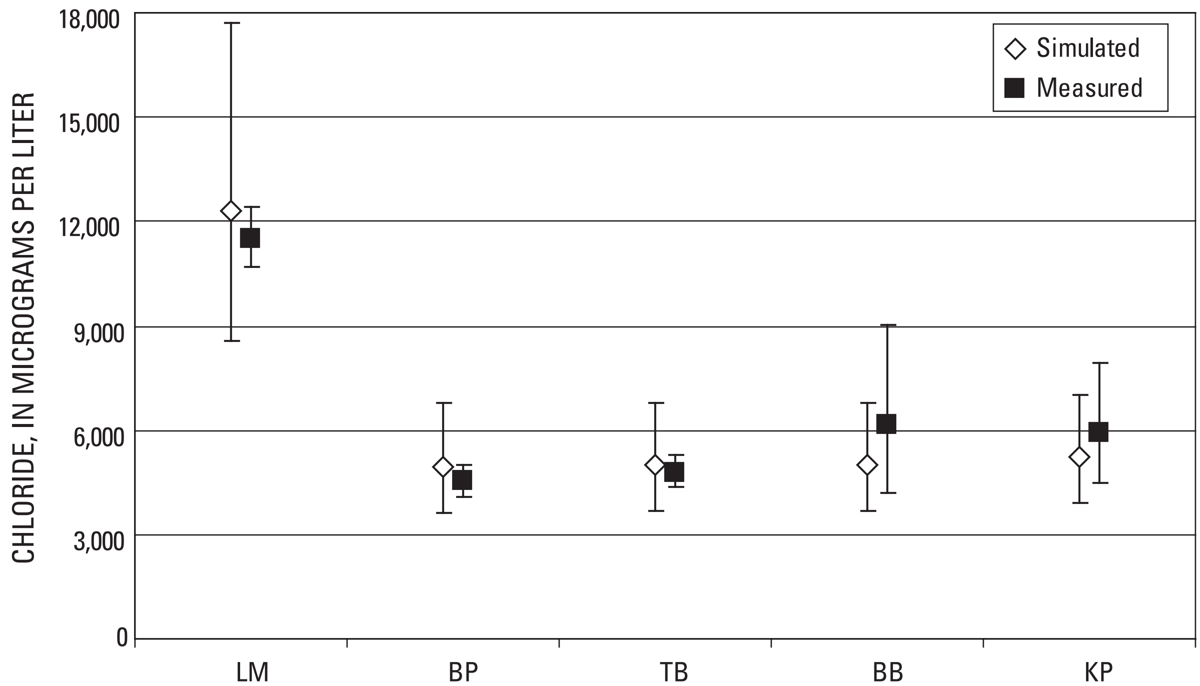


Figure 6. Measured and simulated chloride concentrations in Lake Mallalieu and Lake St. Croix pools (summer average, May–September, 1999) used to determine calibration factors for dispersion between adjacent pools in BATHTUB model [LM, Lake Mallalieu; BP, Bayport Pool; TB, Troy Beach Pool; BB, Black Bass Pool; KP, Kinnickinnic Pool].

values are shown by the vertical bars (plus and minus one standard error) on each data point. On the basis of these comparisons, the calibration factor for dispersion between Lake Mallalieu and the Bayport Pool was set to 0.0, which represents no upstream dispersion from the Bayport Pool into Lake Mallalieu. This is reasonable given that the dam and head difference between these pools prevents all upstream mixing. The calibration factors for dispersion between the Bayport Pool and Troy Beach Pool, and the Troy Beach Pool and the Black Bass Pool were set to 0.5, which represents limited upstream mixing between these pools. The calibration factor for dispersion between the Black Bass Pool and the Kinnickinnic Pool was set to 0.7, which represents slightly more upstream mixing than between the other pools. More mixing may occur between the Kinnickinnic and Black Bass Pools than between the other pools because of backwater from the Mississippi River. The resulting simulated and measured chloride concentrations are shown in figure 6.

Algorithms and Calibration

Within BATHTUB, several algorithms are available to simulate each water-quality constituent. The algorithms chosen to simulate nutrient and chlorophyll *a* concentrations in Lake Mallalieu and the Lake St. Croix pools are listed in table 11. All of the default algorithms within BATHTUB, except that for simulating total nitrogen, provided reasonable results and, therefore, were used. The only algorithm that accurately simulated total nitrogen concentrations was the first-order settling velocity algorithm. Within BATHTUB, calibration coefficients for each water-quality constituent may be applied for each pool; however, no site-specific calibrations were applied.

Comparison Between Simulated and Measured Water Quality

With the data from May–September, 1999 (flow from each tributary and that estimated for each unmon-

Table 11. Algorithms used within BATHTUB to simulate water quality in Lake Mallalieu/Lake St. Croix pools

Process	Model number within BATHTUB	Algorithm description
Phosphorus balance	1	Second order, available phosphorus
Nitrogen balance	7	Settling velocity
Chlorophyll *a* concentration	2	Phosphorus, light, and flushing rate
Secchi depth	1	Chlorophyll *a* and turbidity
Dispersion	1	Fisher numeric
Phosphorus calibration	1	Decay rates
Nitrogen calibration	0	None

itored area, and the volumetrically weighted nutrient concentrations computed from the respective loads and flows, table 4), BATHTUB was used to simulate the water quality in Lake Mallalieu and the Lake St. Croix pools. Water-quality data measured in Lake Mallalieu and the Lake St. Croix pools in 1999 are compared with that simulated with BATHTUB in figure 4. As in figure 6, an estimate of the certainty of the measured and simulated values are shown by the vertical bars (plus and minus one standard error) on each data point. Estimates of the certainty in the simulated response in each water-quality constituent in the figures that follow had relatively similar estimates of certainty as shown in figure 4; however, the confidence limits are not displayed.

In general, simulated water quality in Lake Mallalieu and the Lake St. Croix pools from BATHTUB was similar to the measured water quality in 1999 (fig. 4). The only discrepancy was in chlorophyll *a* concentrations in Lake Mallalieu, where chlorophyll *a* concentrations were underestimated by BATHTUB. This discrepancy was probably caused by the high non-algal turbidity in Lake Mallalieu. A site-specific calibration could have been applied to adjust the simulated chlorophyll *a* concentrations in Lake Mallalieu; however, instead the response in chlorophyll *a* concentrations are described in terms of a percent change from a base condition.

Response in Water Quality to Changes in Phosphorus Loading

To simulate water-quality changes in Lake Mallalieu and the Lake St. Croix pools in response to basin-wide changes in phosphorus loading, the average volumetrically weighted total and dissolved ortho-phosphorus concentrations for each tributary (monitored and unmonitored) and direct point source were decreased and increased for each of the three flow regimes. Phosphorus concentrations were decreased by 50, 25, and 10 percent, and increased by 10, 25, 50, 75, 100, 150, and 200 percent (the actual phosphorus concentrations are given in the Appendix). Nitrogen concentrations were not altered in the various flow regimes or the various phosphorus loading scenarios. Since Lake Mallalieu and the Lake St. Croix pools are phosphorus limited, altering nitrogen concentrations should have little effect on the simulated results. Additional simulations conducted with adjusted nitrogen concentrations confirmed this assumption. Decreases and increases in phosphorus loading were examined in these three types of years to determine whether the water quality in Lake Mallalieu and the Lake St. Croix pools responds differently to changes in phosphorus loading during different flow regimes.

Changes in Phosphorus Concentrations

On the basis of model results for the 1999 flow regime, phosphorus concentrations in Lake Mallalieu and the Lake St. Croix pools have a relatively linear response to a linear change in phosphorus loading (fig. 7); however, the changes in phosphorus concentrations in the pools are not expected to be as large as the changes in phosphorus loadings. Changes in phosphorus concentrations in the pools should be about one-half that of the changes in phosphorus loading. In other words, a 100-percent increase in phosphorus loading should result in a 40- to 65-percent increase in phosphorus concentrations. This non-linear response may be caused partly by the assumption that loadings from precipitation and sediment release do not change during different flow regimes, and partly by increased settling of nutrients associated with higher loading.

Changes in phosphorus concentrations in response to changes in phosphorus loading should vary amongst the pools in Lake St. Croix, with the largest response in the Bayport Pool and the smallest response in the Kinnickinnic Pool (fig. 7). The decreasing phosphorus concentrations from the Bayport Pool to the Kinnickinnic Pool observed in 1999 and simulated by BATHTUB (fig. 4) should still occur with increases and most decreases in phosphorus loading. With a decrease in loading by 50 percent, all of the pools should have similar phosphorus concentrations. However, as phosphorus loading increases, the downstream differences in concentration become more extreme because phosphorus concentrations in the Bayport Pool are more responsive than the downstream pools.

BATHTUB simulations for wet and dry years indicate that phosphorus concentrations in Lake Mallalieu and the Lake St. Croix pools should respond to variable phosphorus loading slightly different from those simulated for the 1999 flow regime (demonstrated for Lake Mallalieu and the Bayport Pool in fig. 8). In dry years, the response should be less extreme, and in wet years, the response should be more extreme. This response was caused by phosphorus concentrations in the tributaries increasing during higher flows and decreasing during lower flows, which is a typical response of streams dominated by non-point sources of phosphorus.

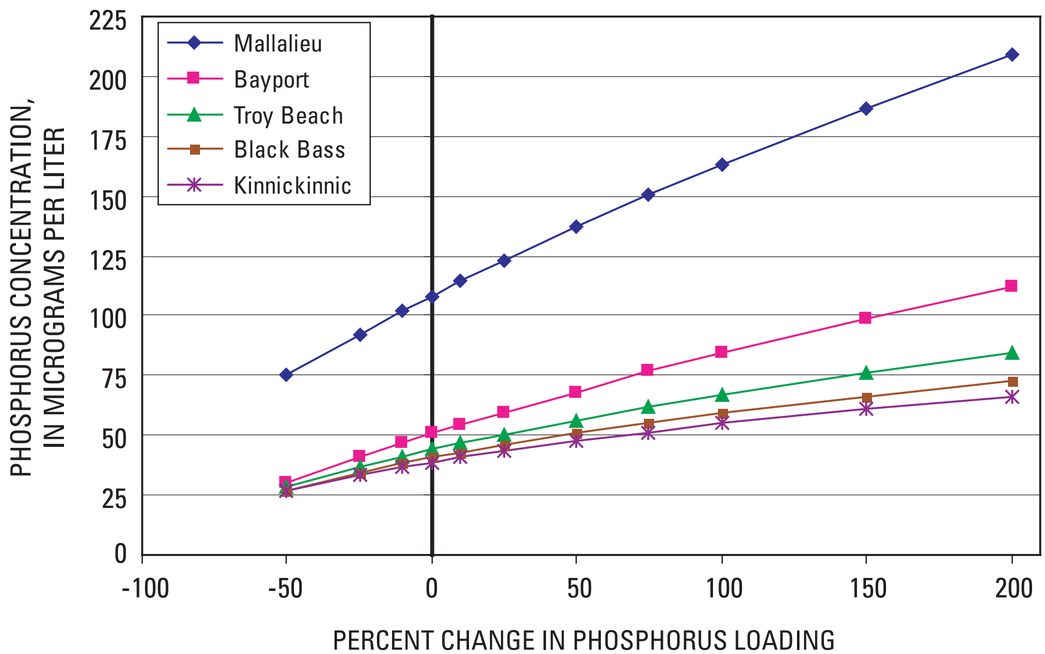
To determine if the changes simulated by the calibrated BATHTUB model in the dry and wet years were reasonable and to further evaluate the model, the simulated total phosphorus concentrations with 0-percent change in loading (figs. 7 and 8) were compared with data collected immediately upstream of the Bayport Pool (Stillwater) and downstream of the Kinnickinnic Pool (Prescott) during dry and wet years (table 12). Total phosphorus concentrations measured in 1996 (the simulated wet year) at both of these sites were higher than in 1988 (the simulated dry year), consistent with that simulated by the model (fig. 8); however, the median total phosphorus concentration measured during the five wettest years from 1977–2000 was only slightly higher than that measured during the five driest years (table 12). The median dissolved ortho-phosphorus concentration measured during the five wettest years from 1977–2000 also was higher at both sites than that measured during the five driest years.

Changes in Chlorophyll *a* Concentrations

On the basis of model results for the 1999 flow regime and variable phosphorus loading, chlorophyll *a* concentrations in Lake Mallalieu and the Lake St. Croix pools have a non-linear response to a linear change in phosphorus loading, with a greater response to reductions in phosphorus loading than to increases in loading (fig. 9). With a 50-percent reduction in loading, chlorophyll *a* concentrations should decrease by about 25 to 30 percent; however, with a 50-percent increase, chlorophyll *a* concentrations should increase by about 15 percent. With a 200-percent increase in loading, chlorophyll *a* concentrations should only increase by about 35 percent. The non-linear response in chlorophyll *a* concentrations associated with the near-linear change in total phosphorus concentrations was expected based on the non-linear relation between phosphorus and chlorophyll *a* concentrations found for other Wisconsin water bodies (Lillie and others, 1993).

Changes in chlorophyll *a* concentrations in response to variable phosphorus loading should be slightly different for the various Lake St. Croix pools. Chlorophyll *a* concentrations in the Bayport Pool should have the greatest response and those in the Kinnickinnic Pool should have the least response (fig. 9). The greater response in chlorophyll *a* concentrations in the Bayport Pool may be due to its greater response in phosphorus concentrations (fig. 7).

On the basis of model results for the simulated dry and wet years, chlorophyll *a* concentrations in Lake Mallalieu and the Lake St. Croix pools should respond to variable phosphorus loading slightly different from those for 1999 flow regime. In Lake Mallalieu, chlorophyll *a* concentrations should be slightly higher in dry and wet years (fig. 10), but the percent changes with increased and decreased phosphorus loading should to be similar to those simulated for the 1999 flow regime (fig. 9). Throughout Lake St. Croix, the response in



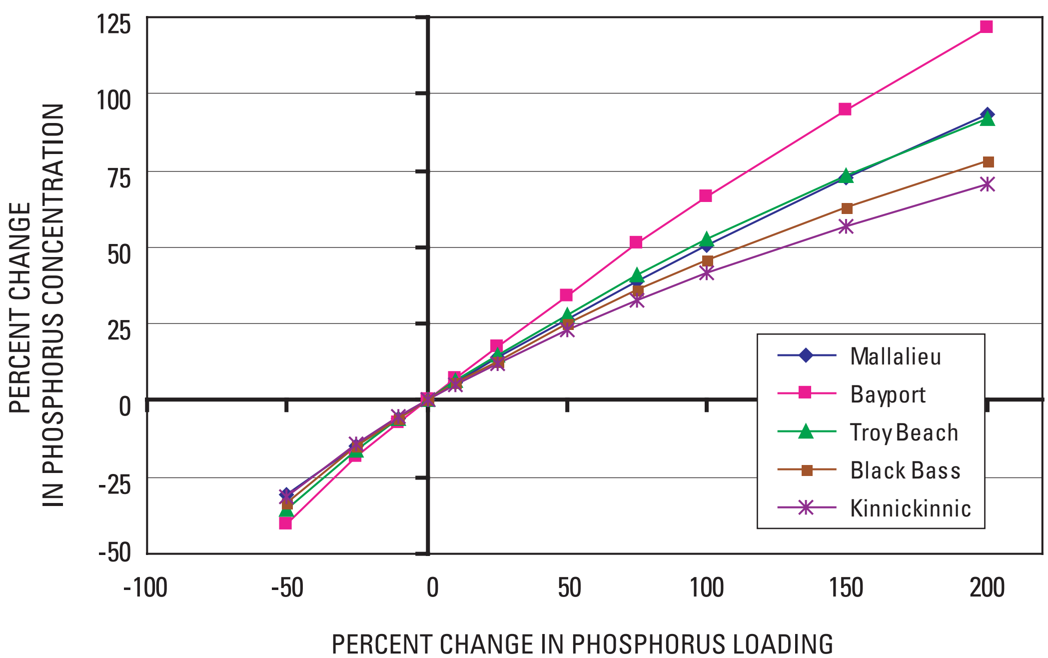


Figure 7. Simulated changes in phosphorus concentrations in Lake Mallalieu and Lake St. Croix pools, in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB for the 1999 flow regime.

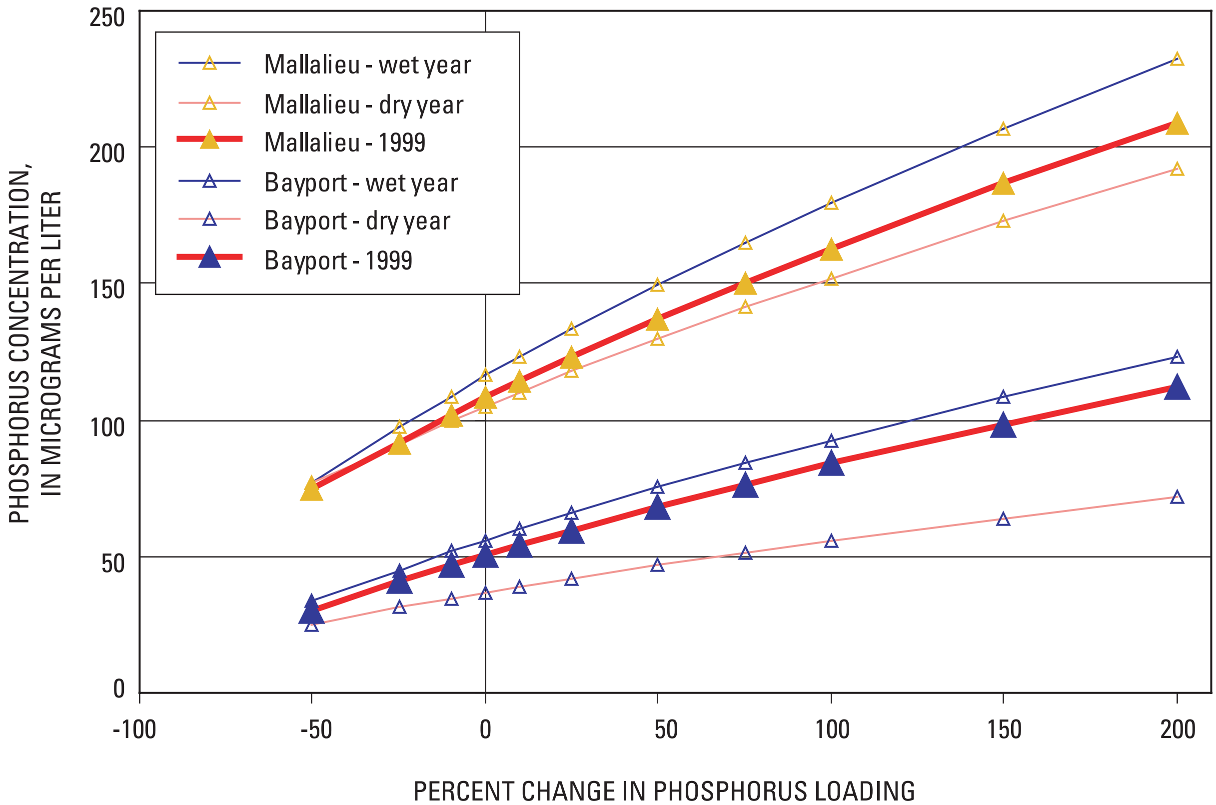


Figure 8. Simulated changes in phosphorus concentrations in Lake Mallalieu and the Bayport Pool for the 1999 flow regime, simulated dry year (flows based on 1988 data), and simulated wet year (flows based on 1996 data) in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB.

chlorophyll *a* concentrations to variable loading in wet years should be similar to those for the 1999 flow regime, but slightly more responsive than concentrations in dry years. The lower chlorophyll *a* concentrations in the dry years were primarily caused by the lower phosphorus concentrations associated with lower flows.

The lower chlorophyll *a* concentrations in the dry year are not consistent with data collected immediately upstream of the Bayport Pool (Stillwater) and downstream of the Kinnickinnic Pool (Prescott) (table 12). The measured data indicate that although total and dissolved phosphorus concentrations decrease during dry years, the increased water-residence time in the pools results in higher chlorophyll *a* concentrations than in wet years when algae are flushed more rapidly through the pools. Therefore, chlorophyll *a* concentrations shown for dry years in figure 10 are expected to be higher than in years with higher flows, but the percentage of change shown in figure 9 may still be valid.

Changes in Water Clarity (Secchi Depths)

On the basis of model results for the 1999 flow regime, Secchi depths (water clarity) in Lake Mallalieu and the Lake St. Croix pools change very little in response to variable phosphorus loading (fig. 11). Changes in phosphorus loading from 50-percent reductions to 200-percent increases should only cause average Secchi depths to change about 0.4 m or less from present conditions. The limited response in Secchi depths may be caused by the high non-algal turbidity and stained water in Lake Mallalieu and Lake St. Croix. The small increase in water clarity from the Bayport Pool to the Kinnickinnic Pool still should be present with any change in phosphorus loading.

In the simulated dry and wet years, average summer Secchi depths in Lake Mallalieu and the Lake St. Croix pools are expected to respond to variable loading similarly to those for the 1999 flow regime (fig. 12). Water clarity may, however, slightly decrease during dry years because of the increase in chlorophyll *a* concentrations not simulated by BATHTUB.

Table 12. Average water quality during May–September measured at Stillwater and Prescott, 1977–2000

[Data were collected by the Metropolitan Council-Environmental Services (MCES); P, phosphorus; µg/L, micrograms per liter; m^3/s, cubic meters per second]

Year	Average flow m^3/s	Total P, µg/L Stillwater	Total P, µg/L Prescott	Dissolved Ortho-P, µg/L Stillwater	Dissolved Ortho-P, µg/L Prescott	Chlorophyll *a*, µg/L Stillwater	Chlorophyll *a*, µg/L Prescott
1977	99.6	53	51	19	26	19	9
1978	174.9	110	55	25	38	10	2
1979	162.0	78	56	46	49	27	13
1980	80.1	55	43	14	26	48	22
1981	152.8	63	54	18	14	31	8
1982	135.6	58	33	12	16	38	24
1983	148.4	78	41	16	8	31	22
1984	213.7	65	135	16	34	35	10
1985	183.1	89	47	16	26	32	12
1986	303.9	54	41	30	46	27	11
1987	68.5	56	26	7	25	43	28
1988	63.4	63	60	8	48	34	20
1989	102.8	52	34	46	39	27	16
1990	123.4	49	55	21	29	26	13
1991	212.1	109	110	56	72	18	5
1992	110.2	55	29	18	99	28	10
1993	184.5	49	37	29	19	15	7
1994	147.5	79	85	24	29	32	18
1995	168.1	100	63	73	14	24	13
1996	162.9	129	32	11	11	22	8
1997	104.4	56	27	18	5	22	11
1998	78.9	63	52	9	15	32	17
1999	157.2	62	50	15	16	23	16
2000	95.2	73	44	16	9	36	23
Median concentration							
Dry years[a]	78.9	63	44	9	25	36	22
Other years	148.0	62	51	18	21	26	13
Wet years[b]	212.1	65	47	29	34	27	10

[a]Five driest years (1980, 1987, 1988, 1998, and 2000).

[b]Five wettest years (1984, 1985, 1986, 1991, and 1993).

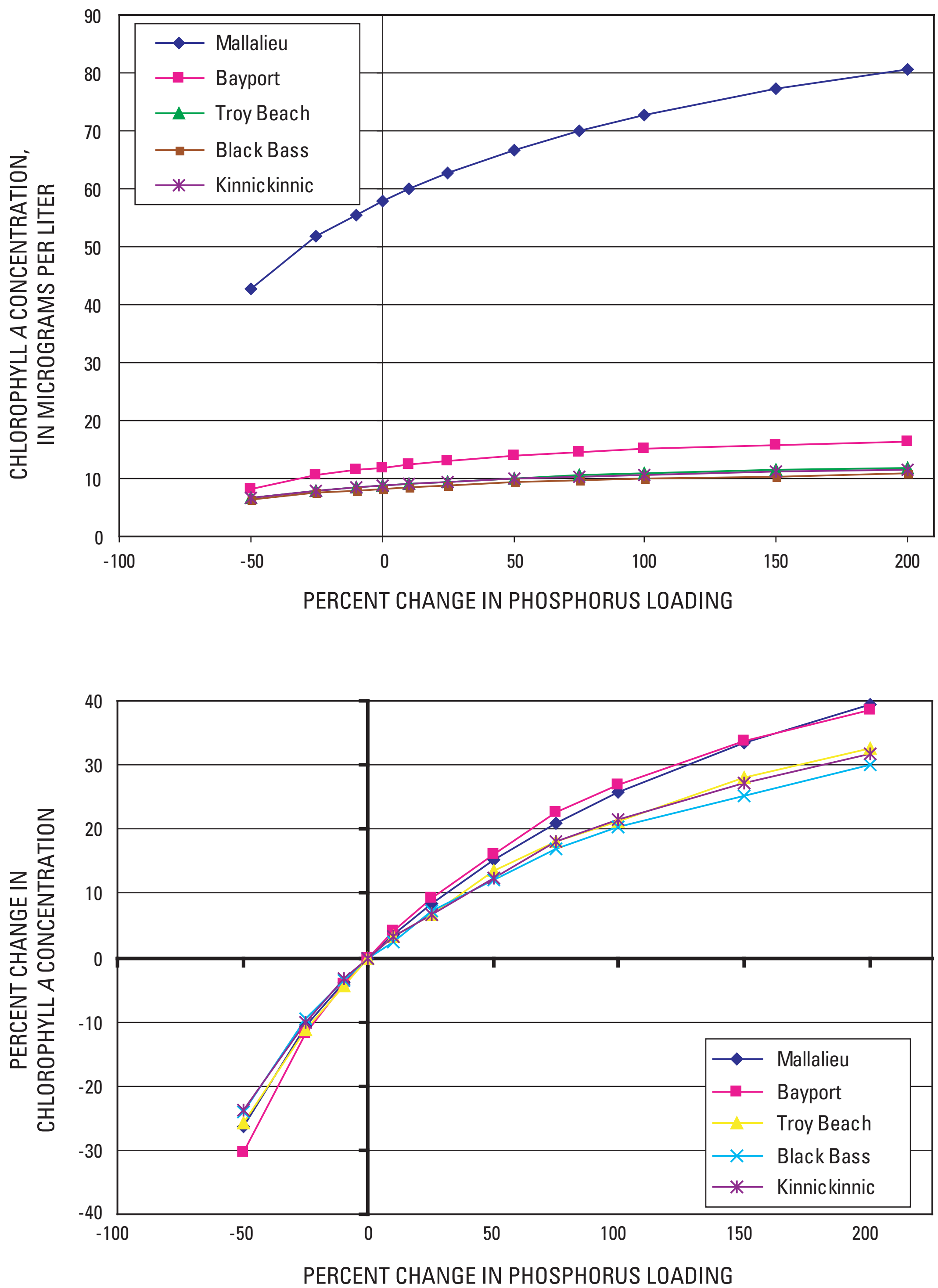


Figure 9. Simulated changes in chlorophyll *a* concentrations in Lake Mallalieu and Lake St. Croix pools in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB for the 1999 flow regime.

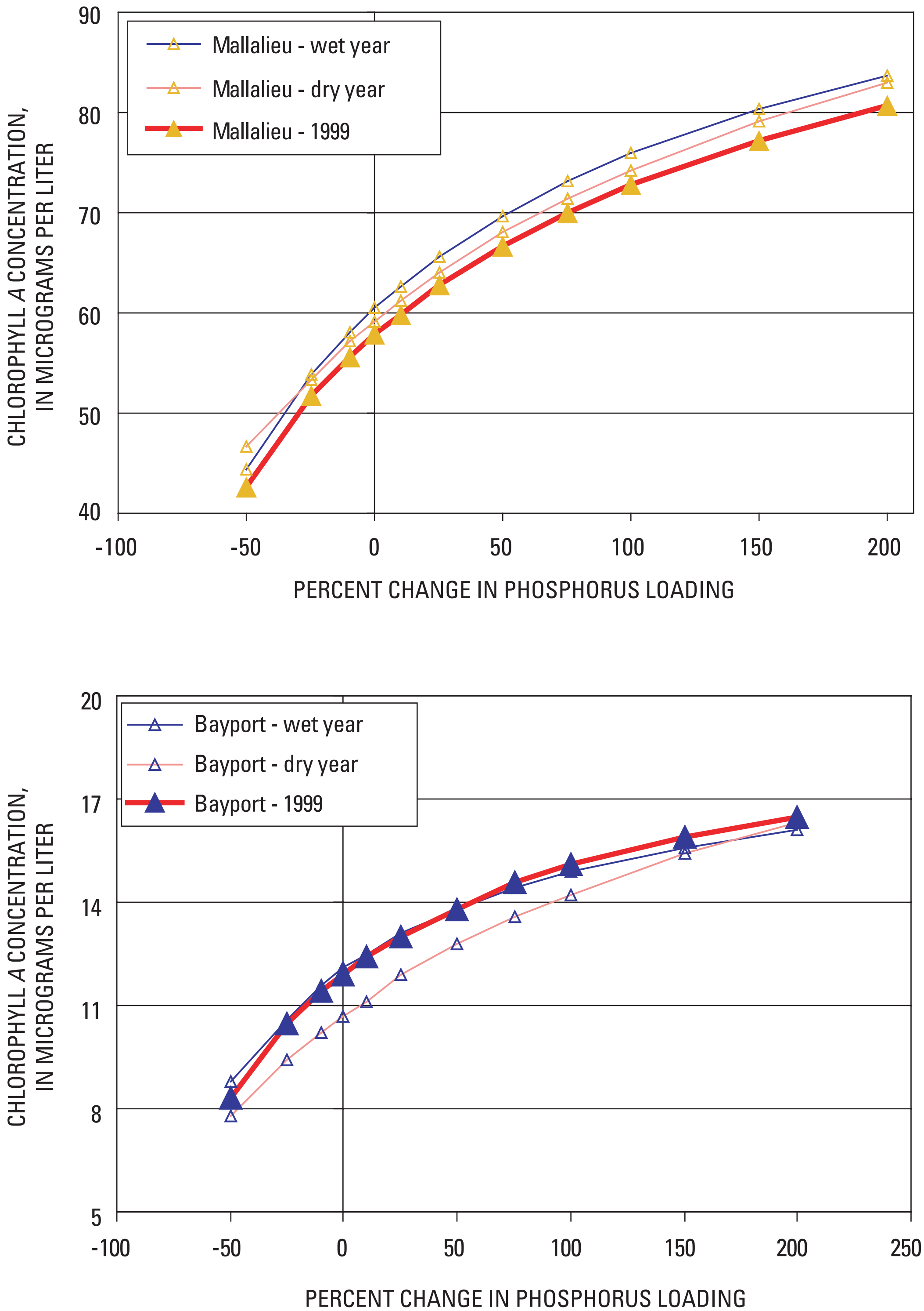
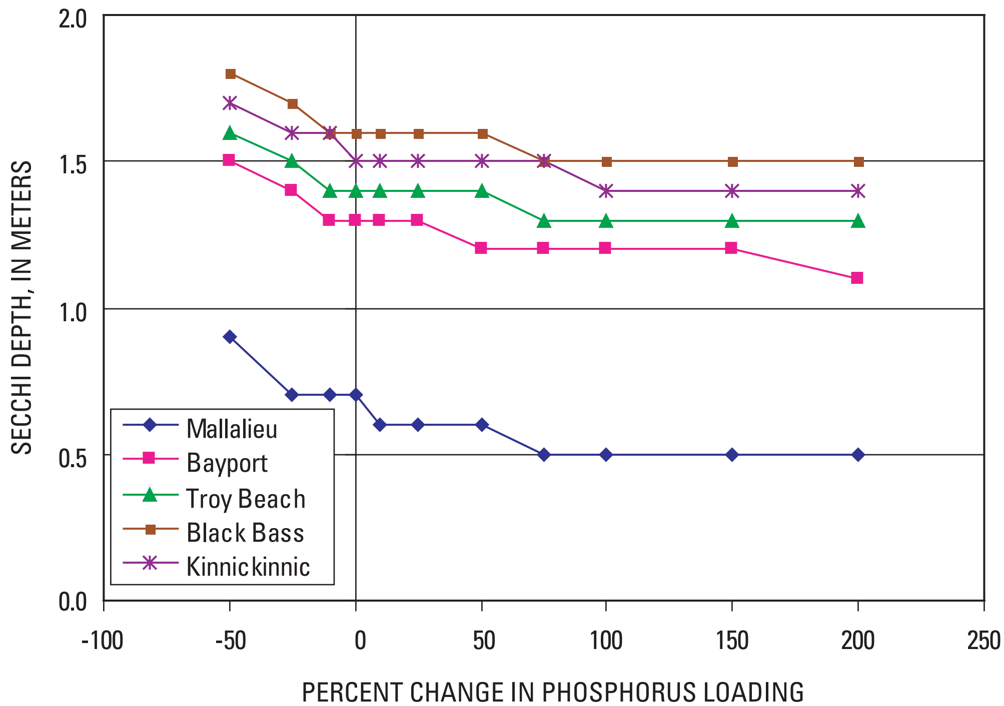


Figure 10. Simulated changes in chlorophyll *a* concentrations in Lake Mallalieu and the Bayport Pool for the 1999 flow regime, a simulated dry year (flows based on 1988 data), and a simulated wet year (flows based on 1996 data) in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB.



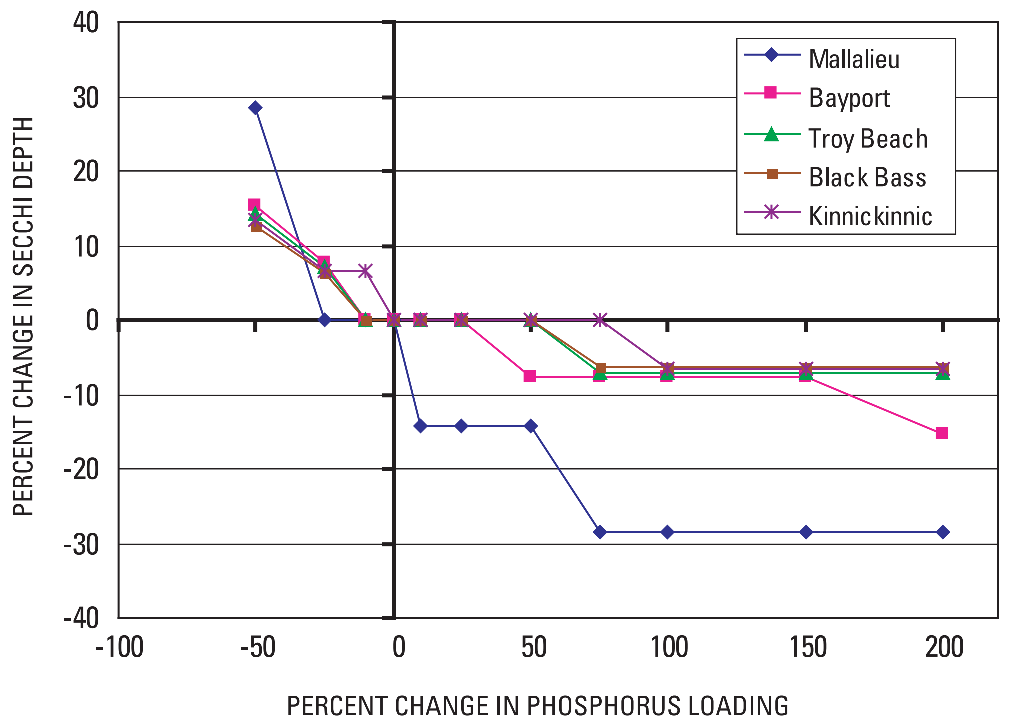


Figure 11. Simulated changes in Secchi depth in Lake Mallalieu and the Lake St. Croix pools in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB for the 1999 flow regime.

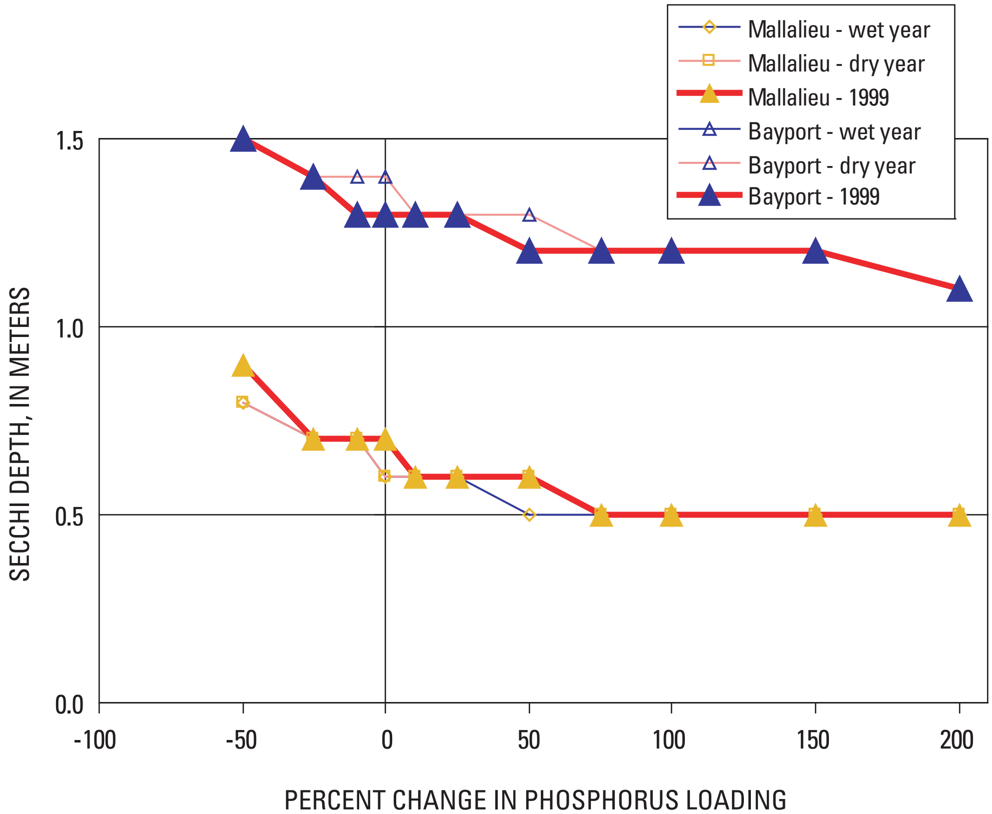


Figure 12. Simulated changes in Secchi depths in Lake Mallalieu and the Bayport Pool for the 1999 flow regime, a simulated dry year (flows based on 1988 data), and a simulated wet year (flows based on 1996 data) in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB.

Changes in Trophic Status

Trophic state index (TSI) values, based on near-surface concentrations of phosphorus and chlorophyll *a*, and on Secchi depths, are used to classify the water quality or productivity of a lake. TSI values allow these three water-quality characteristics to be placed on similar scales. Oligotrophic lakes (TSI values less than 40) have a limited supply of nutrients, and are typically clear with low algal populations and phosphorus concentrations. Mesotrophic lakes (TSI values between 40 and 50) have a moderate supply of nutrients, are not especially clear, and are prone to moderate algal blooms. Eutrophic lakes (TSI values greater than 50) are nutrient rich with correspondingly severe water-quality problems, such as frequent seasonal algal blooms, and have poor water clarity. Lakes with TSI values greater than 60–70 are considered hypereutrophic, and have very high nutrient concentrations and high algal turbidity.

Trophic state index values indicate that Lake Mallalieu is hypereutrophic and each of the Lake St. Croix pools is eutrophic (0-percent change in phosphorus loading in fig. 13). On the basis of model results, even with 50-percent reductions in phosphorus loading, Lake Mallalieu will remain eutrophic, with TSI values generally greater than 65. The trophic status of the Lake St. Croix pools will respond to changes in phosphorus loading, especially phosphorus-load reductions. Phosphorus-load reductions of 25–50 percent will result in most of Lake St. Croix approaching the mesotrophic-eutrophic range based on total phosphorus and chlorophyll *a* concentrations. However, due to the high nonalgal turbidity and stained water in the lake, Secchi depths will remain very low and result in TSI values that classify the lake as eutrophic.

Changes in Algal Bloom Response

Currently, algal blooms are a common occurrence in Lake Mallalieu, but occur less frequently in Lake St.

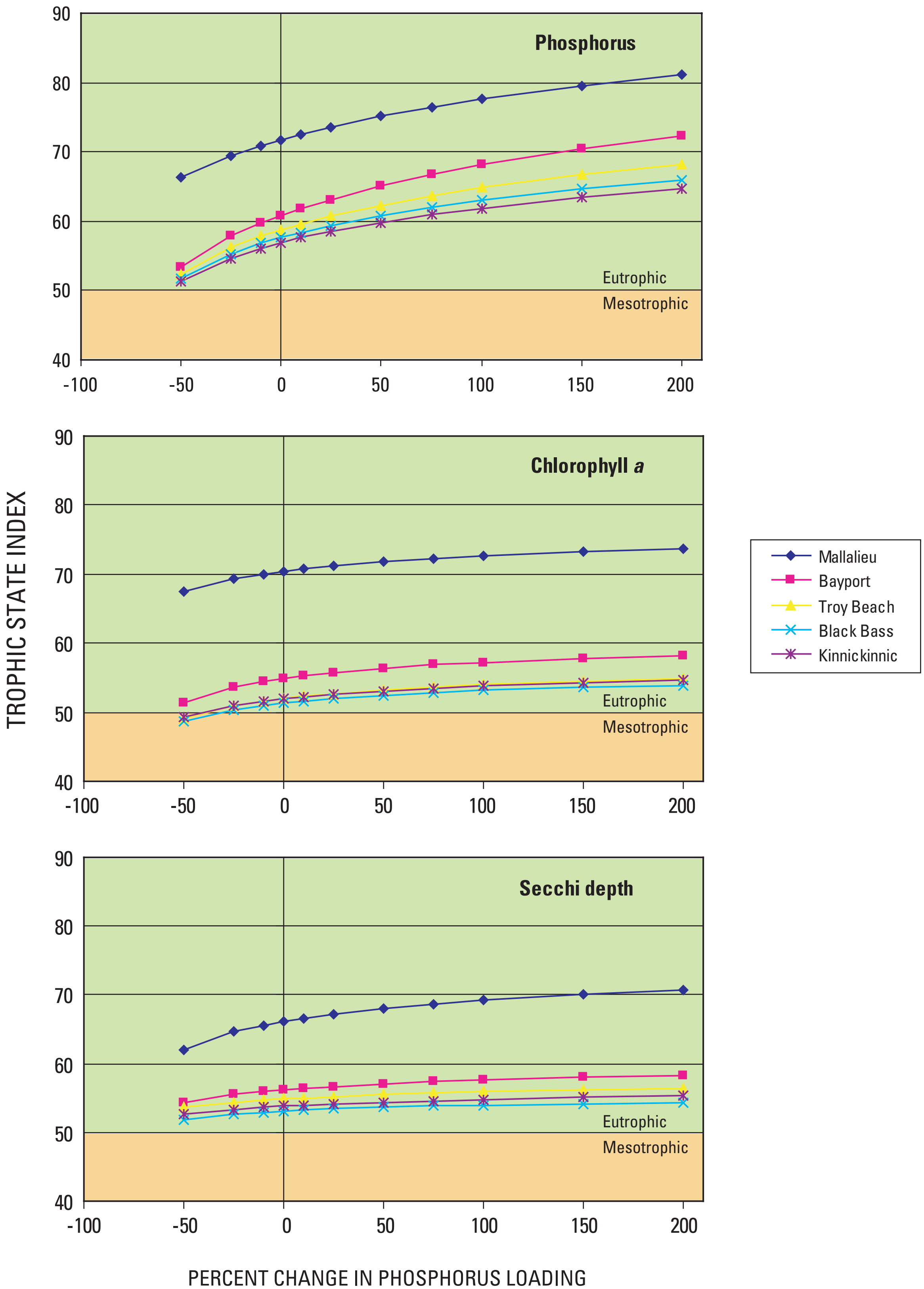


Figure 13. Simulated changes in trophic state index values in Lake Mallalieu and the Lake St. Croix pools in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB for the 1999 flow regime.

Croix. The definition of what constitutes the occurrence of an algal bloom can be site specific and subjective. A chlorophyll *a* concentration of 10 µg/L represents a small amount of algae in a water body, whereas a concentration of 60 µg/L represents an extremely severe algal bloom. A chlorophyll *a* concentration of 30 µg/L represents what many would consider a moderate algal bloom. Figure 14 demonstrates how the occurrence of algal blooms (percent of days from May through September with a chlorophyll *a* concentration exceeding a certain value) responds to variable phosphorus loading based on how an algal bloom is defined (10 to 60 µg/L of chlorophyll *a*) in Lake Mallalieu, and the Bayport, Troy and Kinnickinnic Pools. A subset of these data are summarized in table 13 for algal blooms defined as chlorophyll *a* concentrations greater than 10, 30, and 60 µg/L.

On the basis of model results for the 1999 flow regime, algal blooms in Lake Mallalieu are common regardless of how an algal bloom is defined. If defined as a chlorophyll *a* concentration greater than 30 µg/L, algal blooms in Lake Mallalieu should presently occur on about 75 percent of the days from May through September (table 13, fig. 14). With a decrease in phosphorus loading by 50 percent, this frequency should decrease to about 60 percent of the time. With an increase in loading by 50 percent, this frequency should increase to about 85 percent of the time, and with an increase of 200 percent, this frequency should increase to about 90 percent of the time. Severe algal blooms, as defined by a chlorophyll *a* concentration greater than 60 µg/L, should presently occur about 35 percent of the time in Lake Mallalieu. With a 50-percent reduction in the phosphorus load, this bloom frequency should decrease to 20 percent of the time. Conversely, with a 200-percent increase in loading, the frequency of severe algal blooms should increase to about 55 percent of the time. In Lake Mallalieu, the number of days that chlorophyll *a* concentrations are above a given threshold should be more than presented here because BATHTUB underestimates the amount of chlorophyll *a* in Lake Mallalieu (fig. 5); however, the relative changes should be correct.

Algal blooms are more frequent in the Bayport Pool than in the three downstream pools (fig. 14 and table 13). On the basis of model results for 1999, algal blooms throughout Lake St. Croix are uncommon unless an algal bloom is defined as a chlorophyll *a* concentration greater than 10 µg/L. With this definition, algal blooms occur about 50 percent of the time between May and September in the Bayport Pool and 30 percent of the time in the other pools. If defined as a chlorophyll *a* concentration greater than 30 µg/L, algal blooms should only occur about 4 percent of the time in the Bayport Pool and about 1 percent of the time in the other pools.

With decreases in phosphorus loading for the 1999 flow regime, the frequency of algal blooms will decrease (fig. 14 and table 13). If a bloom is defined as a chlorophyll *a* concentration greater than 10 µg/L, a decrease in phosphorus loading by 50 percent should decrease the frequency of algal blooms to less than 30 percent of the time in the Bayport Pool and to less than 20 percent of the time in the other pools (compared to about 30 to 50 percent of the time with no load reduction). If defined as a chlorophyll *a* concentration greater than 30 µg/L, a 50-percent load reduction should decrease the occurrence of algal blooms to less than 1 percent of the time anywhere in Lake St. Croix (compared to 1 to 4 percent of the time with no load reduction).

With increases in phosphorus loading, algal bloom frequency will increase throughout Lake St. Croix. If blooms are defined as a chlorophyll *a* concentration greater than 10 µg/L, a 50-percent increase in loading should cause algal blooms to occur about 60 percent of the time in the Bayport Pool, and about 40 percent of the time in the other pools (compared to about 30 to 50 percent of the time with no load reduction). With a 200-percent increase in loading, algal blooms should occur about 70 percent of the time in the Bayport Pool and about 50 percent of the time in the other pools. If defined as a chlorophyll *a* concentration greater than 30 µg/L, a 50-percent increase in loading should cause algal blooms to occur about 6 percent of the time in the Bayport Pool and about 2 percent of the time in the other pools (compared to 1 to 4 percent of the time with no load reduction). With a 200-percent increase in loading, moderate algal blooms should occur about 10 percent of the time in the Bayport Pool and about 3 percent of the time in the other pools.

On the basis of model simulations for the dry and wet years, the response in the frequency of algal blooms in Lake Mallalieu and the Lake St. Croix pools to variable phosphorus loading only differs slightly from that for the 1999 flow regime. In Lake Mallalieu, algal blooms should be slightly more frequent in dry and wet years, but the percent change for different loading scenarios should be similar to that for the 1999 flow regime (fig. 15). Throughout Lake St. Croix, model simulations

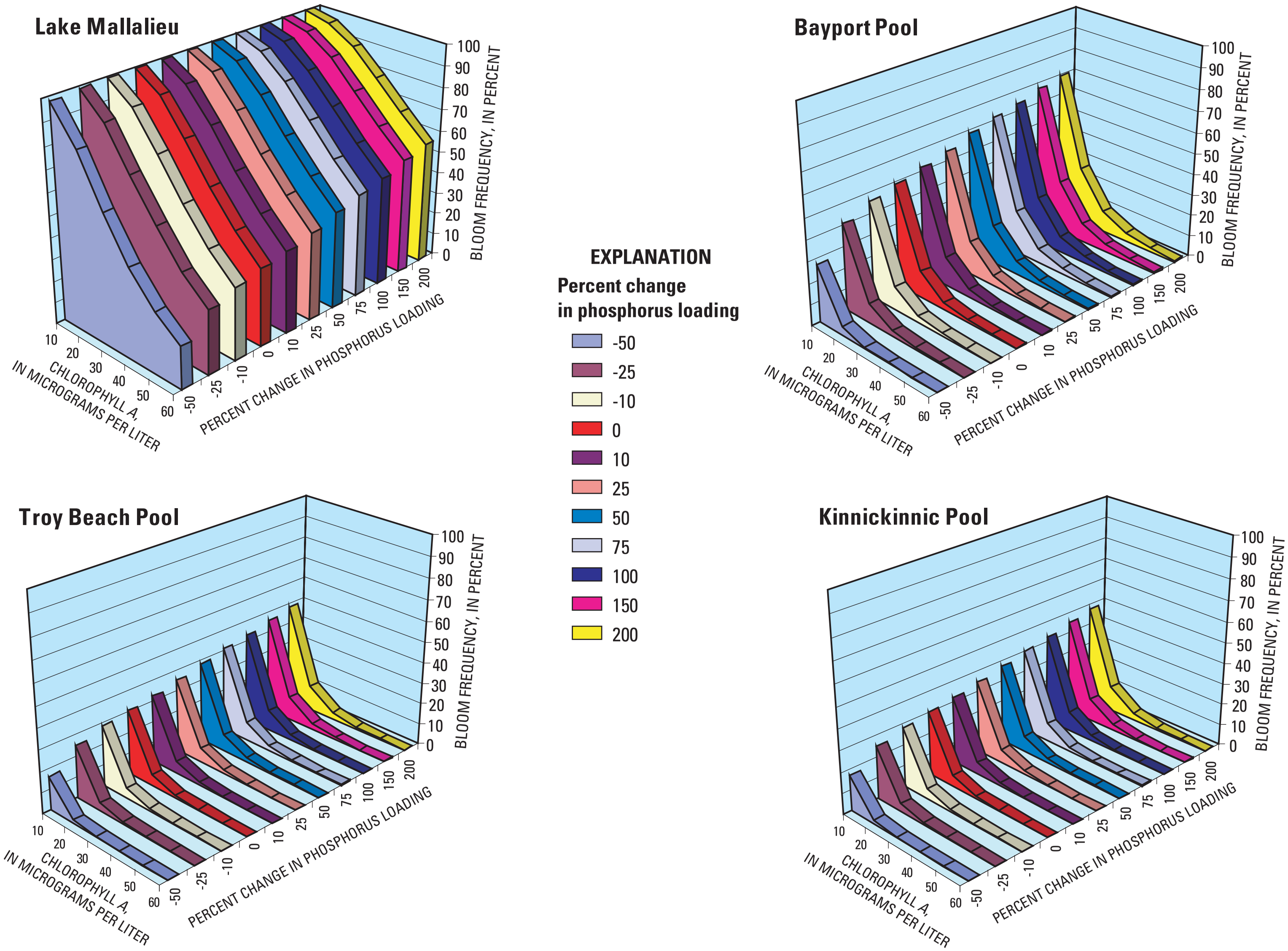


Figure 14. Simulated changes in the frequency (percent of days from May through September) of algal blooms (as defined by different chlorophyll *a* concentrations) in Lake Mallalieu and the Lake St. Croix pools in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB for the 1999 flow regime.

Table 13. Simulated algal bloom frequency in Lake Mallalieu and throughout Lake St. Croix in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB

[Algal blooms defined as chlorophyll *a* concentrations greater than (>) 10, 30, and 60 micrograms per liter (μg/L)]

Percent change in phosphorus loading	Percent of days (from May through September) with algal blooms in indicated pool				
	Mallalieu	Bayport	Troy Beach	Black Bass	Kinnickinnic
			> 10 μg/L		
-50	97.9	27.0	16.1	14.5	16.8
0	99.4	48.8	30.6	26.9	30.2
50	99.7	58.5	38.1	33.4	37.4
100	99.8	63.8	42.8	37.7	42.0
150	99.9	67.0	45.8	40.4	45.0
200	99.9	69.2	48.0	42.4	47.3
			> 30 μg/L		
-50	60.2	0.9	0.3	0.2	0.3
0	77.4	3.6	1.1	0.8	1.1
50	83.6	6.0	1.9	1.4	1.8
100	86.9	7.8	2.5	1.8	2.4
150	88.8	9.1	3.0	2.2	2.9
200	90.1	10.2	3.4	2.5	3.3
			> 60 μg/L		
-50	19.5	0.0	0.0	0.0	0.0
0	35.7	0.2	0.0	0.0	0.0
50	44.4	0.4	0.1	0.0	0.1
100	50.1	0.6	0.1	0.1	0.1
150	53.9	0.7	0.1	0.1	0.2
200	56.6	0.8	0.2	0.1	0.2

indicate that changes in the frequency of algal blooms in wet years should be similar to those estimated for the 1999 flow regime. Results of model simulations also indicate a decreased frequency of algal blooms throughout Lake St. Croix in dry years; however, measured chlorophyll *a* concentrations were higher during dry years than in moderate and wet years (table 12). Therefore, the frequency of algal blooms during dry years are expected to be higher than shown in figure 15; however, the relative changes for different loading scenarios (shown in figure 14) are likely to still be valid.

SUMMARY AND CONCLUSIONS

Each of the St. Croix River pools is currently eutrophic because of high nutrient loading. The water-quality model, BATHTUB, was used to better understand anticipated changes in water quality and trophic status of each of the pools in response to basinwide changes in phosphorus loading. The model was first calibrated by use of water-quality and flow data collected throughout the basin from 1997–99. The model was then applied to the pools with various basinwide changes in phosphorus loading during three different flow regimes: 1999, a simulated dry year (flows based on 1988 data), and a simulated wet year (flows based on 1996 data).

On the basis of model results, the water quality of each of the pools will respond to changes in phosphorus loading. Linear increases in phosphorus loads should cause: linear increases in phosphorus concentrations in all of the St. Croix River pools (although phosphorus concentrations in the pools will change at a smaller rate than the change in loading); non-linear increases in chlorophyll *a* concentrations (with a smaller relative response with higher phosphorus loading); the frequency of algal blooms to increase (a greater response in severe blooms), and water clarity to decrease slightly. The relative response in water quality should be very similar regardless of the flow regime, although phosphorus concentrations should be slightly lower in dry years than in wet years because phosphorus concentra-

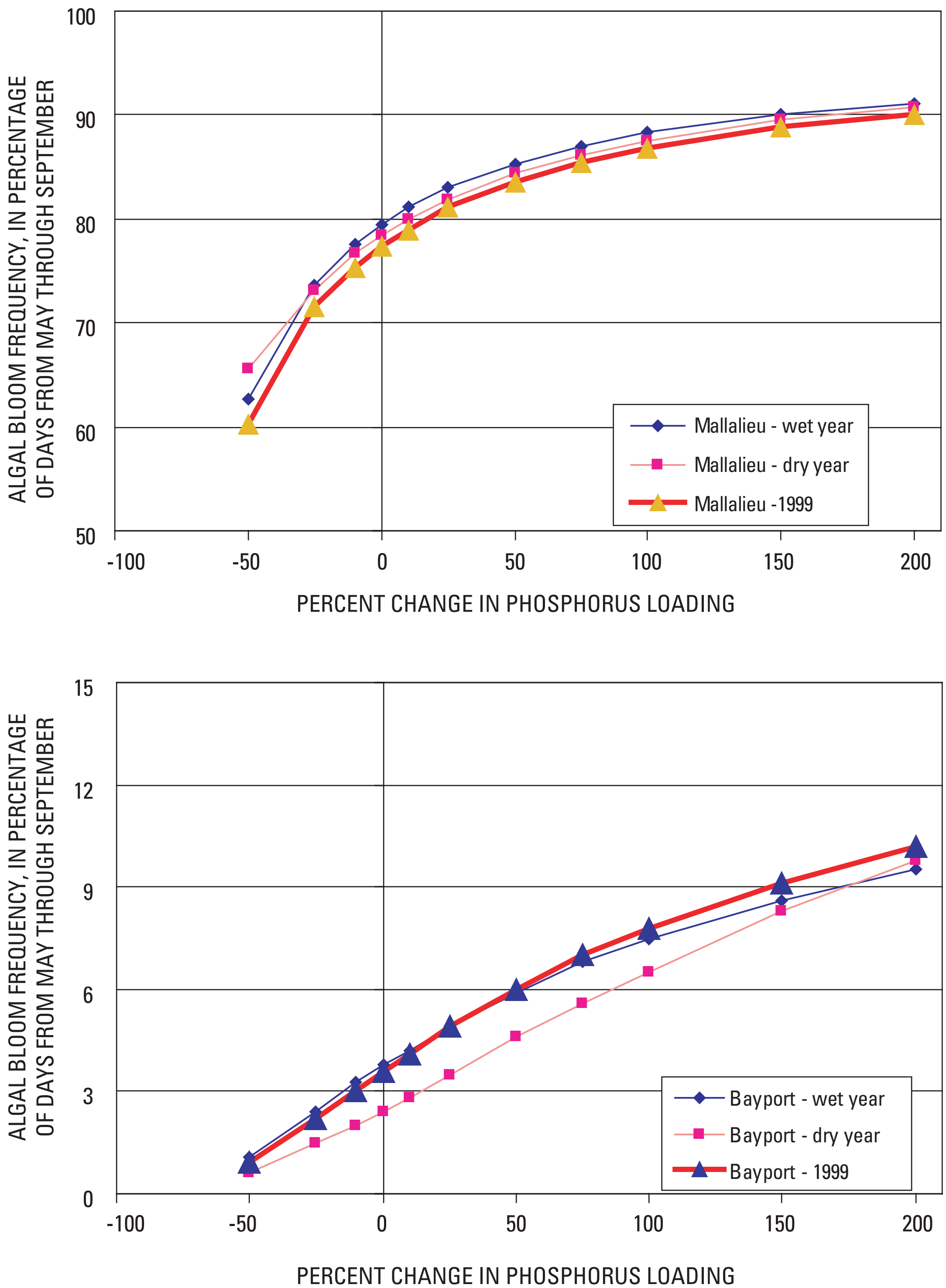


Figure 15. Simulated changes in algal bloom frequency (defined as the percent of days from May through September with chlorophyll *a* concentrations greater than 30 µg/L) in Lake Mallalieu and the Bayport Pool for the 1999 flow regime, a simulated dry year (flows based on 1988 data), and a simulated wet year (flows based on 1996 data) in response to various phosphorus-loading scenarios, on the basis of output from BATHTUB.

tions in most tributaries increase with increasing flow, and chlorophyll *a* concentrations should be higher in dry years than in wet years because of the increased water-residence time.

About a 50-percent reduction in phosphorus loading is required for the Lake St. Croix pools to be classified as mesotrophic with respect to phosphorus and chlorophyll *a* concentrations, whereas a larger reduction in phosphorus loading is needed for Lake Mallalieu to be classified as mesotrophic. Even with these reductions, however, water clarity in each of the pools will remain poor because of the high non-algal turbidity and stained water.

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APPENDIX

Appendix. Volumetrically-weighted total phosphorus concentrations, in micrograms per liter, for various phosphorus loading scenarios for the flows of 1999, a simulated dry year (flows based on 1988 data), and simulated wet year (flows based on 1996 data) computed from loads estimated with flow-to-load relations

[TP, total phosphorus; DOP, dissolved ortho-phosphorus; monitored, monitored area in 1999; unmonitored, unmonitored area; WWTP, wastewater treatment plant; POTW, publicly owned treatment works]

			Load reduction						Load increase													
	Base		50 percent		25 percent		10 percent		10 percent		25 percent		50 percent		75 percent		100 percent		150 percent		200 percent	
Stream	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP
1999 - Flow regime																						
Willow River monitored	86	29	43	15	64	22	77	26	94	32	107	37	128	44	150	51	171	59	214	73	257	88
Lake Mallalieu unmonitored (Willow)	86	29	43	15	64	22	77	26	94	32	107	37	128	44	150	51	171	59	214	73	257	88
St. Croix River monitored	41	13	20	7	31	10	37	12	45	15	51	17	61	20	72	23	82	27	102	33	123	40
St. Croix River unmonitored	41	13	20	7	31	10	37	12	45	15	51	17	61	20	72	23	82	27	102	33	123	40
Apple River monitored	64	18	32	9	48	14	58	16	71	20	80	23	96	27	113	32	129	36	161	46	193	55
Apple River unmonitored	64	18	32	9	48	14	58	16	71	20	80	23	96	27	113	32	129	36	161	46	193	55
Browns Creek monitored	238	79	119	39	179	59	214	71	262	86	298	98	357	118	417	137	476	157	595	196	714	236
Valley Creek monitored	81	27	40	14	61	20	73	24	89	30	101	34	121	41	142	47	162	54	202	68	243	81
Troy Beach Pool unmonitored (Apple)	64	18	32	9	48	14	58	16	71	20	80	23	96	27	113	32	129	36	161	46	193	55
Black Bass Pool unmonitored (Willow)	86	29	43	15	64	22	77	26	94	32	107	37	128	44	150	51	171	59	214	73	257	88
Kinnickinnic River monitored	86	60	43	30	64	45	77	54	94	66	107	76	129	91	150	106	171	121	214	151	257	181
Kinnickinnic Pool unmonitored (Kinnickinnic)	86	60	43	30	64	45	77	54	94	66	107	76	129	91	150	106	171	121	214	151	257	181
Osceola Hatchery	70	70	35	35	53	53	63	63	77	77	88	88	105	105	123	123	140	140	175	175	210	210
Osceola WWTP	4,696	4,604	2,348	2,302	3,522	3,453	4,226	4,144	5,166	5,064	5,870	5,755	7,044	6,906	8,218	8,057	9,392	9,208	11,740	11,510	14,088	13,812
St. Croix Falls Hatchery	117	83	59	42	88	62	105	75	129	91	146	104	176	125	205	145	234	166	293	208	351	249
St. Croix Falls POTW	3,418	2,760	1,709	1,380	2,564	2,070	3,076	2,484	3,760	3,036	4,273	3,450	5,127	4,140	5,982	4,830	6,836	5,520	8,545	6,900	10,254	8,280
Stillwater POTW	341	307	171	154	256	230	307	276	375	338	426	384	512	461	597	537	682	614	853	768	1,023	921
Taylor POTW	2,162	1,946	1,081	973	1,622	1,460	1,946	1,751	2,378	2,141	2,703	2,433	3,243	2,919	3,784	3,406	4,324	3,892	5,405	4,865	6,486	5,838
Hudson WWTP	3,953	3,486	1,977	1,743	2,965	2,615	3,558	3,137	4,348	3,835	4,941	4,358	5,930	5,229	6,918	6,101	7,906	6,972	9,883	8,715	11,859	10,458

Appendix. Volumetrically-weighted total phosphorus concentrations, in micrograms per liter, for various phosphorus loading scenarios for the flows of 1999, a simulated dry year (flows based on 1988 data), and simulated wet year (flows based on 1996 data) computed from loads estimated with flow-to-load relations—Continued

[TP, total phosphorus; DOP, dissolved ortho-phosphorus; monitored, monitored area in 1999; unmonitored, unmonitored area; WWTP, wastewater treatment plant; POTW, publicly owned treatment works]

			Load reduction						Load increase													
	Base		50 percent		25 percent		10 percent		10 percent		25 percent		50 percent		75 percent		100 percent		150 percent		200 percent	
Stream	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP
Simulated dry year																						
Willow River monitored	75	24	38	12	56	18	68	22	83	26	94	30	113	36	132	42	150	48	188	60	226	72
Lake Mallalieu unmonitored (Willow)	75	24	38	12	56	18	68	22	83	26	94	30	113	36	132	42	150	48	188	60	226	72
St. Croix River monitored	22	11	11	6	17	8	20	10	24	12	28	14	33	17	39	19	44	22	55	28	66	33
St. Croix River unmonitored	22	11	11	6	17	8	20	10	24	12	28	14	33	17	39	19	44	22	55	28	66	33
Apple River monitored	42	21	21	10	32	15	38	19	46	23	53	26	63	31	74	36	85	41	106	52	127	62
Apple River unmonitored	42	21	21	10	32	15	38	19	46	23	53	26	63	31	74	36	85	41	106	52	127	62
Browns Creek monitored	156	89	78	45	117	67	141	80	172	98	195	111	234	134	274	156	313	178	391	223	469	267
Valley Creek monitored	53	30	27	15	40	23	48	27	58	33	66	38	80	45	93	53	106	61	133	76	159	91
Troy Beach Pool unmonitored (Apple)	42	21	21	10	32	15	38	19	46	23	53	26	63	31	74	36	85	41	106	52	127	62
Black Bass Pool unmonitored (Willow)	75	24	38	12	56	18	68	22	83	26	94	30	113	36	132	42	150	48	188	60	226	72
Kinnickinnic River monitored	63	48	32	24	47	36	57	43	69	53	79	60	95	72	110	84	126	96	158	120	189	144
Kinnickinnic Pool unmonitored (Kinnickinnic)	63	48	32	24	47	36	57	43	69	53	79	60	95	72	110	84	126	96	158	120	189	144
Osceola Hatchery	70	70	35	35	53	53	63	63	77	77	88	88	105	105	123	123	140	140	175	175	210	210
Osceola WWTP	4,696	4,604	2,348	2,302	3,522	3,453	4,226	4,144	5,166	5,064	5,870	5,755	7,044	6,906	8,218	8,057	9,392	9,208	11,740	11,510	14,088	13,812
St. Croix Falls Hatchery	117	83	59	42	88	62	105	75	129	91	146	104	176	125	205	145	234	166	293	208	351	249
St. Croix Falls POTW	3,418	2,760	1,709	1,380	2,564	2,070	3,076	2,484	3,760	3,036	4,273	3,450	5,127	4,140	5,982	4,830	6,836	5,520	8,545	6,900	10,254	8,280
Stillwater POTW	341	307	171	154	256	230	307	276	375	338	426	384	512	461	597	537	682	614	853	768	1,023	921
Taylor POTW	2,162	1,946	1,081	973	1,622	1,460	1,946	1,751	2,378	2,141	2,703	2,433	3,243	2,919	3,784	3,406	4,324	3,892	5,405	4,865	6,486	5,838
Hudson WWTP	3,953	3,486	1,977	1,743	2,965	2,615	3,558	3,137	4,348	3,835	4,941	4,358	5,930	5,229	6,918	6,101	7,906	6,972	9,883	8,715	11,859	10,458

Appendix. Volumetrically-weighted total phosphorus concentrations, in micrograms per liter, for various phosphorus loading scenarios for the flows of 1999, a simulated dry year (flows based on 1988 data), and simulated wet year (flows based on 1996 data) computed from loads estimated with flow-to-load relations—Continued

[TP, total phosphorus; DOP, dissolved ortho-phosphorus; monitored, monitored area in 1999; unmonitored, unmonitored area; WWTP, wastewater treatment plant; POTW, publicly owned treatment works]

			Load reduction						Load increase													
	Base		50 percent		25 percent		10 percent		10 percent		25 percent		50 percent		75 percent		100 percent		150 percent		200 percent	
Stream	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP	TP	DOP
Simulated wet year																						
Willow River monitored	94	34	47	17	70	25	84	30	103	37	117	42	140	51	164	59	187	68	234	84	281	101
Lake Mallalieu unmonitored (Willow)	94	34	47	17	70	25	84	30	103	37	117	42	140	51	164	59	187	68	234	84	281	101
St. Croix River monitored	47	14	24	7	35	10	43	12	52	15	59	17	71	21	83	24	94	27	118	34	142	41
St. Croix River unmonitored	47	14	24	7	35	10	43	12	52	15	59	17	71	21	83	24	94	27	118	34	142	41
Apple River monitored	72	18	36	9	54	13	64	16	79	19	90	22	107	26	125	31	143	35	179	44	215	53
Apple River unmonitored	72	18	36	9	54	13	64	16	79	19	90	22	107	26	125	31	143	35	179	44	215	53
Browns Creek monitored	265	76	133	38	199	57	239	68	292	83	331	95	398	114	464	133	530	151	663	189	795	227
Valley Creek monitored	90	26	45	13	68	19	81	23	99	28	113	32	135	39	158	45	180	51	225	64	270	77
Troy Beach Pool unmonitored (Apple)	72	18	36	9	54	13	64	16	79	19	90	22	107	26	125	31	143	35	179	44	215	53
Black Bass Pool unmonitored (Willow)	94	34	47	17	70	25	84	30	103	37	117	42	140	51	164	59	187	68	234	84	281	101
Kinnickinnic River monitored	141	85	71	43	106	64	127	77	155	94	176	107	212	128	247	149	282	170	353	213	423	256
Kinnickinnic Pool unmonitored (Kinnickinnic)	141	85	71	43	106	64	127	77	155	94	176	107	212	128	247	149	282	170	353	213	423	256
Osceola Hatchery	70	70	35	35	53	53	63	63	77	77	88	88	105	105	123	123	140	140	175	175	210	210
Osceola WWTP	4,696	4,604	2,348	2,302	3,522	3,453	4,226	4,144	5,166	5,064	5,870	5,755	7,044	6,906	8,218	8,057	9,392	9,208	11,740	11,510	14,088	13,812
St. Croix Falls Hatchery	117	83	59	42	88	62	105	75	129	91	146	104	176	125	205	145	234	166	293	208	351	249
St. Croix Falls POTW	3,418	2,760	1,709	1,380	2,564	2,070	3,076	2,484	3,760	3,036	4,273	3,450	5,127	4,140	5,982	4,830	6,836	5,520	8,545	6,900	10,254	8,280
Stillwater POTW	341	307	171	154	256	230	307	276	375	338	426	384	512	461	597	537	682	614	853	768	1,023	921
Taylor POTW	2,162	1,946	1,081	973	1,622	1,460	1,946	1,751	2,378	2,141	2,703	2,433	3,243	2,919	3,784	3,406	4,324	3,892	5,405	4,865	6,486	5,838
Hudson WWTP	3,953	3,486	1,977	1,743	2,965	2,615	3,558	3,137	4,348	3,835	4,941	4,358	5,930	5,229	6,918	6,101	7,906	6,972	9,883	8,715	11,859	10,458