Establishing a Chlorophyll *a* Goal for a Run-of-the-river Reservoir

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ABSTRACT

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Lake Pepin, a 100 km² run-of-the-river reservoir, is located on the Mississippi River about 80 km downstream of the Twin Cities metropolitan area on the border between Wisconsin and Minnesota. A major inter-agency study of Lake Pepin and the Mississippi River has been underway since 1990 for the purposes of determining the impacts of the effluent from the Metropolitan Waste Control Commission's Metropolitan Wastewater Treatment Facility on Lake Pepin and to predict the benefits of reducing effluent phosphorus levels to 1 mg L^{-1} or lower. Severe nuisance algal blooms and fish kills during the low flows of 1988 prompted this study.

Understanding the reservoir limnology and factors contributing to user perception of "nuisance algal blooms" (in terms of chlorophyll *a* concentration or phytoplankton species composition), are important steps in developing a chlorophyll *a* goal for Lake Pepin. Based upon analyses of chlorophyll *a* data, phytoplankton composition, and user perception information, a summer mean chlorophyll *a* concentration of 30 mg m^{-3} is recommended as a water quality goal for Lake Pepin. Nutrient-mass balance modeling suggests that a dramatic reduction in the inflow phosphorus concentration and in the overall in-lake phosphorus concentration (including internal loading) will be required to achieve this goal during low-flow summers.

Key Words: phosphorus, reservoir, goal setting, chlorophyll *a*, hydraulic residence time, user perception.

Lake Pepin is a run-of-the-river reservoir on the Mississippi River 80 km downstream of the Twin Cities metropolitan area, between Wisconsin and Minnesota (Fig. 1). An inter-agency study of Lake Pepin and the Mississippi River has been underway since 1990 in response to water quality problems. The purpose of the study is to determine impacts of effluent from the Metropolitan Waste Control Commission (MWCC) Wastewater Treatment Facility (Metro WWTF) and predict benefits of reducing phosphorus to 1 mg L^{-1} of P or less. The Metro WWTF discharges about 250 MGD and is the largest WWTF in Minnesota. Total phosphorus concentrations in the effluent are generally 2 - 3 mg L^{-1}.

Minnesota's "phosphorus rule" requires dischargers to treat effluent to 1 mg P or lower if discharge is direct to a lake or reservoir (MN Statutes, 1994). When discharge is not direct, as in the case of Lake Pepin, it is generally necessary to assess whether it affects lakes or reservoirs downstream. In this paper specific objectives for examining the water quality of this reservoir and establishing a chlorophyll a (chl *a*) goal include:

1. Develop/adapt empirical models for predicting nuisance algal blooms from in-lake phosphorus and other controlling factors, and link these models to relations between phosphorus loading (external and internal) and in-lake phosphorus concentrations. For this task historic and current data were used to develop relations between chl *a* and in-lake total phosphorus (TP), water residence time, and other factors.

2. Define "nuisance algal blooms", expressed in terms of chl *a* concentration, exceedance frequencies, and/or algal species composition. For this task Lake Pepin chl *a* and algal composition data were analyzed, user perceptions from adjacent ecoregions were examined, Lake Pepin volunteer monitor user survey data were reviewed and compared to chl *a* and Secchi

data, and surveys of citizens residing near the lake were conducted. Log-normal frequency distributions were used to predict frequency of algal blooms as a function of summer-mean chl *a*.

Study Area

Lake Pepin was formed by the deposition of sand and sediment at the mouth of the Chippewa River (Fig. 1). Lake Pepin bathymetry and spatial variations in water quality suggest the presence of two distinct lake segments, referred to as the upper and lower segments, as noted on Fig. 2. The upper segment is much shallower (mean depth of 3.6 m) than the lower segment (mean depth of 6.6 m) and accounts for 28 percent of the lake by volume. Lake Pepin has a watershed area of approximately 122,000 km^2, draining about 50-55 percent of Minnesota and a portion of northwestern Wisconsin (Fig. 1). Three major drainage basins - the Upper Mississippi (to Lock and Dam 1), Minnesota, and St. Croix contribute about 96 percent of the flow (as measured at Prescott, Wisconsin) on an annual basis and account for about 96 percent of the drainage area (to Lock and Dam 3) (Table 1). The large watershed area promotes short water residence times that range from 6 to 47 days. Lake Pepin's water quality and flushing rate depend primarily on the quality and quantity of water from the Mississippi River.

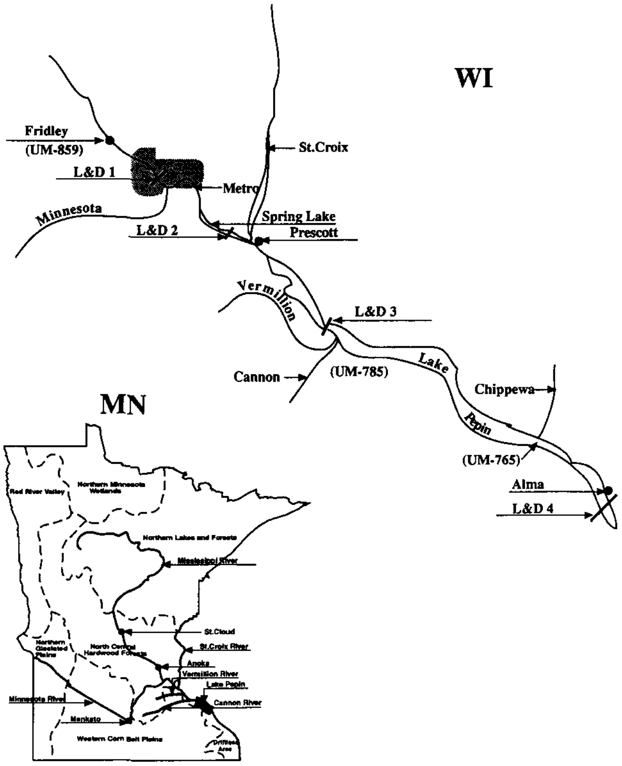

Figure 1.—Mississippi River phosphorus study area.

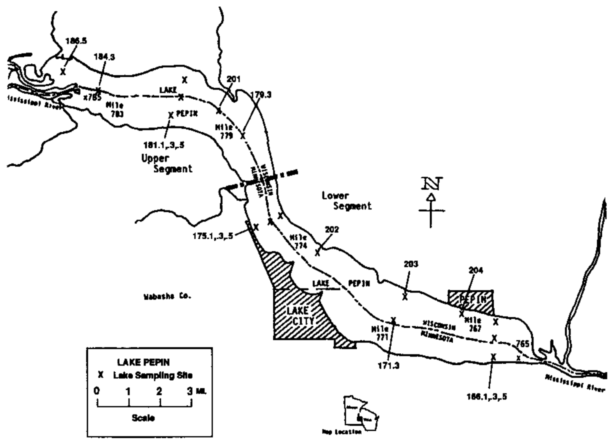

Figure 2.—Lake Pepin sampling sites.

Methods

Monitoring Program

An intensive monitoring program was conducted by the Minnesota Pollution Control Agency (MPCA) in conjunction with the Minnesota Department of Natural Resources (MDNR) between April 1990 and September 1992. Samples were collected at 13 sites in Lake Pepin (Fig. 2). Transects of three sites each were sampled at river miles UM-766, 775, and 781. Samples were collected weekly or biweekly between April and September and monthly between October and March by MDNR staff using a depth-integrated sampler (2 meter PVC tube with 3.2 centimeter diameter). Near-bottom samples (approximately 0.2 meters from bottom) were also collected using a horizontal, Van Dorn sampler. TP samples were acidified and all samples were stored on ice. Samples for chl *a* and pheophytin a analysis were filtered and frozen before delivery to the Minnesota Department of Health Environmental Lab. TP (STORET # 665) and ortho-P (STORET #70507) were measured by EPA Methods 365.4 and 365.2 (EPA 1983). Corrected chl *a* (STORET #32211) was measured according to EPA (1973) and Standard Methods 17th ed. (APHA 1985). A Beckman Model Du-6 spectrophotometer with a 2 nm band width was used. Total suspended solids (STORET #530) and total suspended volatile solids (STORET #535) were measured by EPA Methods 160.2 and 160.4 (EPA 1983).

Dissolved oxygen and temperature were measured with a Yellow Springs Instruments Model 57 DO meter. Field turbidity was measured with a Hach Model 16800 Portlab Turbidimeter. Secchi disk transparency was measured using a disk mounted on a calibrated pole.

Table 1.—Lake Pepin morphometric and watershed characteristics.

	English	Metric
Surface area[1]	39.7 mi²	102.7 km²
Mean depth	17.7 ft	5.4 m
Maximum depth	56 ft	17 m
Width (variable)	~1-2 mi	~1.7-3.3 km
Fetch (maximum)	~11.8 mi	19 km
Length	20.8 mi	33.5 km
Volume	448,000 a-f	553 x 10^6 m³
Watershed area	48,600mi²	122,000 km²
Mean hydraulic retention time (on an annual basis)	9 days	

Phytoplankton samples were collected throughout the monitoring period. Phytoplankton were identified and enumerated using standard inverted microscope techniques (APHA 1992), with counts expressed in units/ml (clump counts as per Standard Method 1002 F(C,1)) and percent composition of dominant algal types based on cell volume.

Additional Data Sources and Analysis

Additional sources of data include: a) MPCA water quality surveys of Lake Pepin from four previous years (1978-1980, 1988); b) MWCC Lake Pepin surveys (1976-1981, one site in each segment of the Lake between river miles UM-779 and 773); c) Wisconsin Department of Natural Resources (WDNR) water quality data collected at Lock and Dam 3 (UM-797) on the Mississippi (~inflow to Lake Pepin) and near the lake outlet (UM-765), and d) USGS flow data collected near Prescott, Wisconsin (UM-811).

Data analyses and modeling efforts were focused on summer (June - September) 1976 to 1991, a period of primary recreational activity and maximum frequency of algal blooms. The years 1976 to 1991 represented a wide range of river flow and loading and were a relevant time frame for development and justification of a new discharge permit for the Metro WWTF.

Model Selection

An important task of this study was to develop a basis for predicting nuisance algal blooms as a function of phosphorus loads and other controlling factors. The empirical model network contained in BATHTUB, a computer program developed for predicting eutrophication in U.S. Army Corps of Engineer reservoirs (Walker 1987), was adapted for application to Lake Pepin using MPCA data from 1978, 1979, 1980, 1988, 1990, and 1991. In contrast to empirical eutrophication models originally developed for northern natural lakes (e.g., Dillon and Rigler 1974, Canfield and Bachmann 1981) the BATHTUB model network accounts for controlling factors other than phosphorus (Fig. 3). Detailed descriptions of model structures are contained in Walker (1987). Sub-routines used in this study are as follows:

1. Phosphorus balance—Model 2, a second order decay P sedimentation model was used. Second order decay models perform better than first order decay models in reservoirs (Walker 1987).

2. Non-algal turbidity, as defined in Walker (1987), is estimated as the inverse of Secchi depth, linearly adjusted for chl *a* (Table 2). It is an empirical term which reflects light attenuation due to the presence of color and inorganic solids in the water column (Walker, 1985b). Secchi transparency was predicted using the BATHTUB Chl *a*/Secchi model, which partitions the inverse of Secchi depth into algal and non-algal components (Walker 1987).

3. Chl *a* Model 2 in BATHTUB was selected for application to Lake Pepin. Criteria for selecting Model 2 are contained in Walker (1987). This model is preferred for systems with short water residence times and high non-algal turbidity. Model 2 predicted chl *a* as a function of TP, non-algal turbidity, mixing depth, and residence time. Mixing depth was calculated based on mean depth (Walker 1987).

4. Extension of the chl *a* model to predict the frequency of algal blooms provides useful management information. Log-normal frequency distributions (Walker 1985*a*) previously have been successfully applied for this purpose. The previously developed models were used to predict frequencies of chl *a* concentrations > 30, > 40, and > 60 µg/L. Two of these instantaneous chl *a* levels have previously been

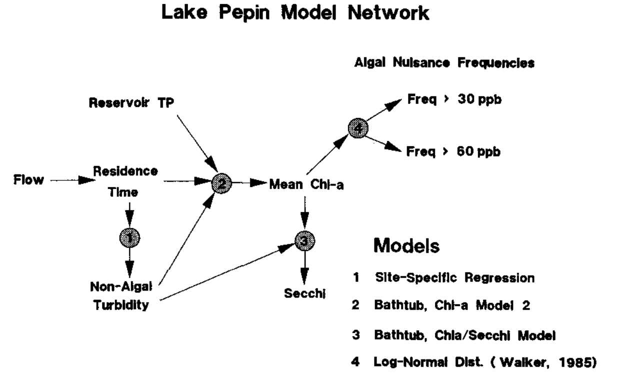

Figure 3.— Lake Pepin Model Network.

associated with user perceptions of water quality; "severe nuisance blooms" (> 30 mg m^{-3}) and "worse yet" conditions (> 60 mg m^{-3}; Heiskary and Walker 1989 and Walmsley 1984).

Criteria Development

TP and chl *a* are commonly used for identifying use impairment related to eutrophication. Both have been used in state rule-making (NALMS 1992). Chl *a* is the better parameter for making direct linkages to nuisance conditions, while phosphorus can be a more appropriate parameter from modeling and source-control standpoints. Criteria may be developed for statewide application, as is the case for Oregon's chl-*a* criteria, or may be waterbody specific, as is the case for Vermont's TP criteria for Lake Champlain (NALMS 1992).

User perception data have been previously used in Minnesota and Vermont (Smeltzer and Heiskary 1990) both for linking user perceptions to measurements of Secchi disk transparency and chl *a* concentrations and water quality criteria development. Four citizens participating in MPCA's Citizen Lake Monitoring Program (CLMP) assisted with data collection on Lake Pepin in 1990. The volunteers made weekly transparency readings and also provided their concurrent perceptions of the "physical appearance" and "suitability for recreation" of the lake on each sampling date at four separate sites on the lake. Their subjective rankings were conducted on a scale of 1 to 5 ranging from (1) "crystal clear" to (5) "severely high algae levels, scums and odors" for physical perception, and from (1) "beautiful" to (5) "no swimming or boating" for recreational suitability. These user perception results were cross-tabulated with Secchi and chl *a* in our analysis.

Results and Discussion

River Flow and Lake Hydraulic Residence Time

Daily flow data from the USGS gage show summer-average flow for the period 1976-1991 ranged from ~5,000 cfs in 1976 to ~35,000 cfs in 1986. Based on the entire period of record (1936-1991) the median summer flow was 13,700 cfs. Because fluctuations in pool level were insignificant, water residence time in Lake Pepin is directly related to river inflow. Summer-average hydraulic residence time ranged from ~6 days (1986) to ~47 days (1976). The median summer-average flow (13,700 cfs) corresponded to a residence time of ~16 days.

Phosphorus Budgets

Flows were paired with concentration data collected

Table 2.—Lake Pepin chlorophyll *a* response model equations.

P =	Reservoir Total P (mg m^{-3})
B =	Reservoir Mean Chlorophyll *a* (mg m^{-3})
B_P =	Phosphorus-Limited Chlorophyll *a* (mg m^{-3})
B* =	Algal Nuisance Level, expressed as Chl *a* conc. (mg m^{-3})
F* =	Frequency Chl *a* > B* (% of samples)
Z =	Standard Normal Deviate
Normal (Z) =	Integral under standard normal curve from minus infinity to Z
G =	Kinetic Factor Used in Chlorophyll *a* Model
Z_{mix} =	Mean Depth of Mixed Layer = 2.7 m
a =	Non-algal Turbidity (1/m)
b =	Secchi/chlorophyll *a* Slope = .02 ($m^2 m^{-1}$)
c =	Chlorophyll *a* Temporal Coefficient of Variation = 0.6
T =	Hydraulic Residence Time (days)
S =	Mean Secchi Depth (m)

Non-Algal Turbidity:

Measured: $a = 1 / S - b B$
Walker (1987)

Predicted: $a' = -0.075 + 7.80 / T$
(Regression: $r^2 = 0.92$, SE = 0.14 1/m)

Mean Chlorophyll *a*:

$$Bp = p^{1.37} / 4.88$$
$$G = Z_{mix} (0.19 + 1.42 / T)$$
$$B = Bp / [(1 + b\,Bp\,G)(1 + a'G)]$$

Secchi Depth:

$$S = 1 / (a' + b B)$$
Walker (1987)

Chlorophyll- *a* Interval Frequency:

Walker (1985)
$$Z = [\ln(B^* / B) + 0.5 c^2] / c$$

$$F^* = [1 - \text{Normal}(Z)] \times 100\ \%$$

at Lock and Dam 3 (UM-797) to calculate loadings into Lake Pepin. Summer-mean TP at Lock and Dam 3 (inflow) averaged 225 µg/L and had an interquartile (IQ) range of 210 to 230 µg/L between 1976 and 1991. Over the same period, lake outflow concentrations averaged 215 µg/L and had an IQ range of 150 to 250 µg/L. The flow-weighted mean inflow TP concentration exceeded outflow concentration in 9 of 14 summers. Increases in TP from the inflow to the outflow tended to occur in summers with average flows less than ~19,000 cfs (70th percentile).

Between 1976 and 1991, summer inflow dissolved ortho-phosphorus (OP) concentrations averaged 102 µg/L with an IQ range of 90 to 110 µg/L. Outflow OP averaged 137 µg/L with an IQ range of 100 to 150 µg/L. Outflow OP concentrations equalled or exceeded inflow concentrations in 11 of 14 summers and outflow concentrations were generally higher in years with lower flow.

Net retention rates, calculated from paired inflow and outflow TP and OP measurements (Fig. 4) indicate strong relationships between phosphorus retention and flow. Negative TP retention (net release from bottom sediments) is indicated for 5 years (1988, 1987, 1980, 1977, 1976), negative OP retention is indicated for 11 years, and positive TP-OP retention (approximates particulate + organic P; Walker 1987) is indicated for all years. These patterns in net retention reflected release of soluble phosphorus from bottom sediments (causing increases in OP) and sedimentation of algal and nonalgal particulate phosphorus from the water column (causing decreases in TP-OP).

In summers with negative TP retention, areal release rates calculated from water-column mass-balances (10-30 mg m^{-2} day^{-1}) approached values (15-20 mg m^{-2} day^{-1}) that have been measured under anaerobic conditions in laboratory microcosm studies using Lake Pepin sediments (James et al. 1992). These calculated release rates were typical of anaerobic lake sediments, despite the fact that anoxic conditions near the water-sediment interface were rarely observed in Lake Pepin. These high release rates were comparable in magnitude to the P loading rate (23 mg m^{-2} day^{-1}) from the Metro WWTF (Fig. 4).

Water Quality

Lake-wide water quality conditions, characterized by MPCA data from 1978-80, 1988, 1990-91 and MWCC data from 1976-77 and 1981, are summarized in Table 3. Sedimentation in the upper segment (Fig. 2), resulted in decreased inorganic suspended solids and increased transparency in the lower segment, particularly under low-flow conditions. For example, during the summers 1978, 1979, 1988, 1990, and 1991, the summer-mean

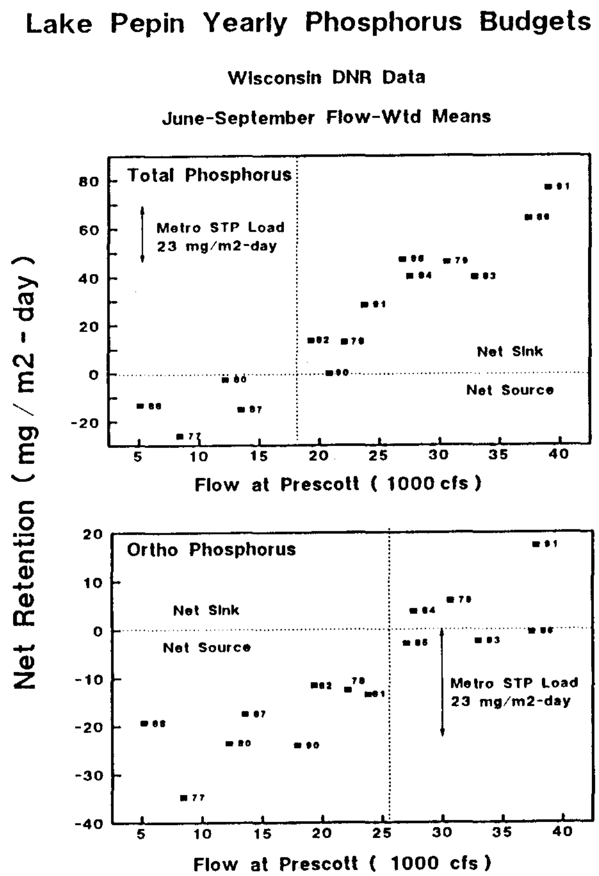

Figure 4.—Lake Pepin yearly phosphorus (P) budgets. P loading was calculated by pairing inflow and outflow P and Mississippi River flows. Inflow P loading minus outflow reflects net retention which is expressed as an areal loading rate based on lake surface area.

inorganic suspended solids (calculated as total suspended solids - total volatile suspended solids) ranged from 12 mg L^{-1} (1979) to 29 mg L^{-1} (1991) in the upper segment. In contrast, inorganic suspended solids ranged only from 4 mg L^{-1} (1979) to 9 mg L^{-1} (1991) in the lower segment. Over the same period summer-mean Secchi ranged from 0.4 m (1991) to 0.6 m (1990) in the upper segment and from 0.7 m (1991) to 0.9 m (1979, 1990) in the lower segment.

During summers when flow was < 10,000 cfs TP concentrations in the lower segment exceeded concentrations in the upper segment by 48 µg/L, 69 µg/L, and 175 µg/L respectively, for 1976, 1977, and 1988. Increases in TP from up- to downstream were primarily in the ortho (soluble-reactive) form. During summers of average- or high-flow, TP decreased slightly and OP increased slightly between the upper and lower segments. For example, in 1990 TP and OP averaged respectively 219 µg/L (standard error, SE= 3) and 111 µg/L (SE=4) in the upper segment and 203 µg/L (SE=4) and 137 µg/L (SE=7) in the lower segment.

Lake-wide summer-mean chl *a* ranged from 57 µg/L in 1988 to 22 µg/L in 1978 (Table 3). Maximum concentrations ranged from 202 µg/L (1988, 1991) to 51 µg/L (1979). In general, summer-mean chl *a* decreased as river flow (flushing rate) increased. Spatial variations in summer-mean chl *a* were also evident, particularly during summers of low-flow (1976, 1988). Chl *a* was higher in the upper segment (summer-means of 63 and 64 µg/L) compared to the lower segment (summer-means of 41 µg/L) during 1976 and 1988. This difference may be in response to the shallower mixed-layer depth of the upper segment (3.5 meters vs. 5.5 meters for the lower segment). This is consistent with the findings of Megard et al. (1978), in their work on the Mississippi River in the Twin Cities Metro area. Differences in chl *a* between segments were less pronounced during summers of average- to high-flow when water residence time of the individual segments was short. For example, in 1978 chl *a* averaged 23 µg/L (SE=3) and 20 µg/L (SE=2) respectively in the upper and lower segments. Based on the individual volumes of the two segments water residence time would have been on the order of two-three days in the upper segment and six-seven days in the lower segment in 1978.

Water residence time can also influence the water quality characteristics of run-of-the-river reservoirs such as Lake Pepin. For example, at short water residence times, there may be inadequate opportunity for nutrient sedimentation via settling of soil particles and/or algal uptake of nutrients and the subsequent settling of the algae (Walker 1987). As water residence time falls below about 10-14 days (for Lake Pepin a 10 day residence time corresponds to river flows of about 24,000 cfs) phytoplankton are removed from the system before the standing crop reaches the level determined by the limiting nutrient (Dillon 1975, Pridmore and McBride 1984) and flushing becomes an important predictor in chl *a* models (Walker 1985a).

Model Results

The model network shown in Fig. 3 provided a basis for predicting changes in important eutrophication response variables — chl *a*, Secchi transparency, and ultimately nuisance algal bloom frequency as a function of TP, water residence time, and inorganic turbidity. This allowed for the establishment of a summer-mean chl *a* goal for the lake and provided an opportunity to evaluate the range of TP loadings and residence times under which the goal may be achieved. The usefulness of the model depends, however, on how well modeled data agree with observed data.

Figs. 5 through 8 provide comparisons of observed vs. predicted values for six summers based on the models used in BATHTUB. Good agreement (r^2) between observed and predicted values was noted for non-algal turbidity and chl *a*. A weaker relation was

Table 3.—Lake Pepin summer water quality. Standard errors are in parentheses.

Year	TP mean (µg/L)	OP mean (µg/L)	Chl *a* mean (µg/L)	Chl *a* max (µg/L)	Secchi mean (m)	Mean Flow (cfs)	Res. Time (days)
1976	185 (15)	—	52 (8)	83	—	4,711	47
1977	312 (32)	192 (48)	31 (8)	58	—	9,965	22
1978	226 (4)	164 (4)	22 (2)	76	0.72	25,253	9
1979	204 (4)	124 (5)	27 (2)	51	0.73	27,621	8
1980	244 (11)	161 (9)	39 (6)	98	0.64	12,174	18
1981	155 (5)	—	37 (4)	54	—	19,389	11
1988	518 (26)	322 (28)	57 (8)	202	0.64	4,921	45
1990	216 (3)	122 (4)	33 (2)	145	0.73	20,009	11
1991	226 (4)	156 (3)	31 (2)	202	0.53	33,516	7

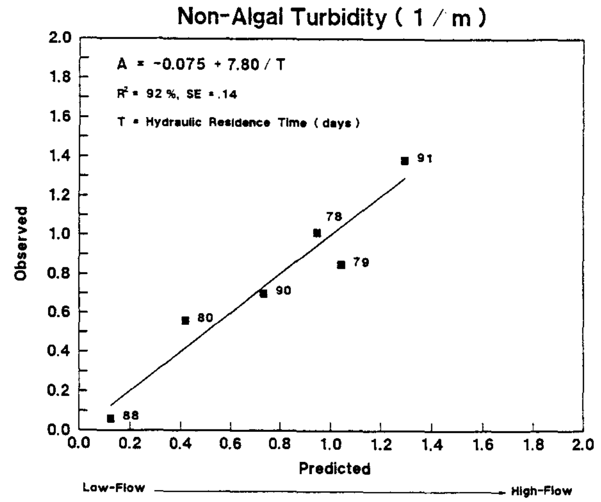

Figure 5.—Summer-mean non-algal turbidity measures for Lake Pepin. For Lake Pepin, non-algal turbidity (calculated as per Table 2) is highly correlated with hydraulic residence time (r^2=0.92) and may be predicted based on hydraulic residence time.

noted (r^2=0.62) for observed vs. predicted Secchi transparency. The relatively low transparency of Lake Pepin (averaged 0.68 m over six summers) was evident. The small range (0.20 m) in summer-mean transparencies between years likely contributed to the low r^2 value (Fig. 7). The log-normal frequency distributions (Walker 1985a) used to predict frequency of algal blooms as a function of summer-mean chl *a* provided good agreement with observed chl *a* interval frequencies (Fig. 8).

Defining Nuisance Algal Conditions

Defining "nuisance algal blooms" in Lake Pepin was an important aspect of this study. Once defined, an appropriate water quality goal based on chl *a* could be established for the Lake. Because of the effect of flow on chl *a* response, an appropriate flow regime for applying the goal was also addressed.

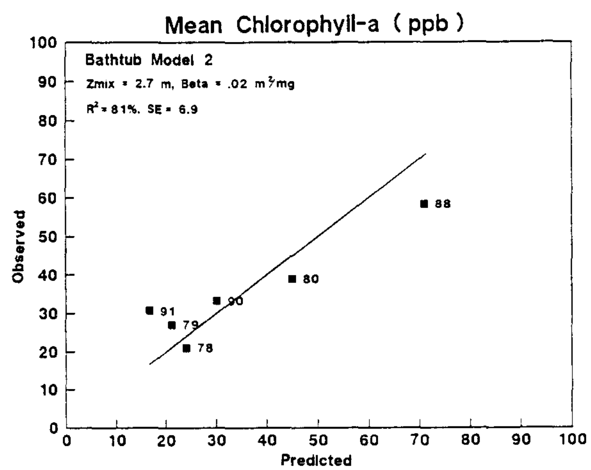

Figure 6.—Observed vs.predicted chlorophyll *a* for Lake Pepin. Chlorophyll *a* is predicted as a function of total phosphorus concentration, non-algal turbidity, mixing depth, and residence time.

Definitions of "acceptable" or "objectionable" lake water quality vary regionally within Minnesota and elsewhere (Heiskary and Walker 1988). Based upon survey data, users of northern Minnesota lakes associate nuisance algal blooms with lower chl *a* concentrations than users of southern lakes (Smeltzer and Heiskary 1990). Because of these regional differences in perception, nuisance algal conditions in Lake Pepin were defined based on ecoregion considerations, citizen interviews conducted by the Minnesota-Wisconsin Boundary Area Commission, Citizen Lake-Monitoring Program (CLMP) volunteer responses in 1990, and chlorophyll *a* and phytoplankton data from Lake Pepin.

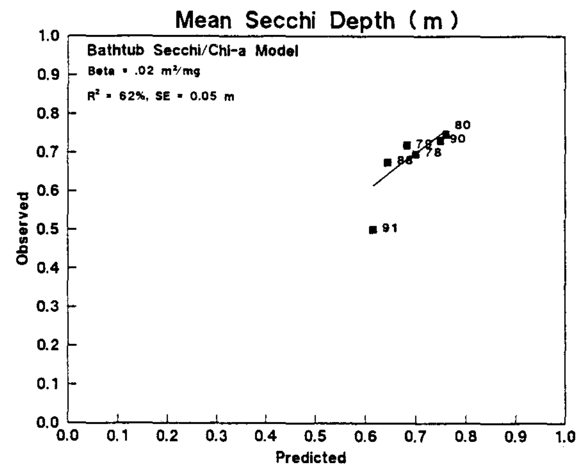

Figure 7.—Observed vs. Predicted Secchi transparency for Lake Pepin. Secchi transparency is predicted based on chlorophyll *a* and non-algal turbidity.

Ecoregion considerations

The geometric mean Secchi transparency associated with perception of "high or severe algae", for two nearby ecoregions, was 1.1 m for the North Central Hardwoods Forest and 0.6 m for the Western Corn Belt Plains (Smeltzer and Heiskary 1990). Typical summer-mean chl *a* for these two ecoregions range from 5-22 µg/L to 30-80 µg/L respectively (Heiskary and Wilson 1989). Considering the range in Lake Pepin's water quality (summer-mean transparency ranges from 0.53-0.73 m and chl *a* ranges from 22-57 µg/L) and its proximity to the Western Corn Belt Plains ecoregion (Fig. 1), user perceptions in Lake Pepin may be somewhat similar. Thus, goal setting should focus on reducing the frequency of severe nuisance algal blooms, as is most frequently the case for lakes in the Western Corn Belt Plains (Heiskary and Wilson 1989).

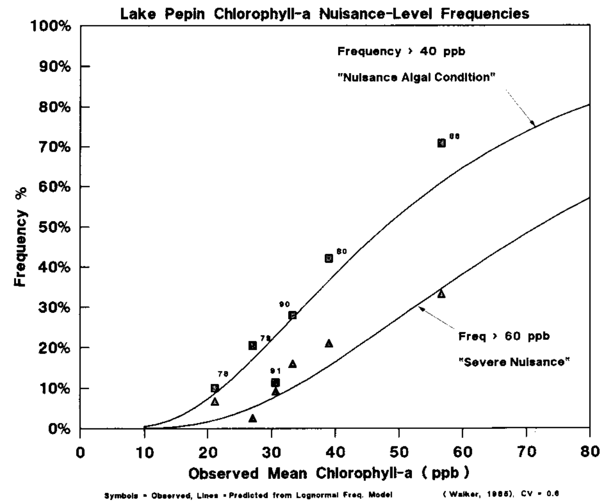

Figure 8.—Chlorophyll *a* Nuisance Level Frequencies for Lake Pepin. Log-normal frequency distributions (Walker, 1985a) have been used to predict frequency of algal blooms as a function of summer-mean chl *a*. Based on six summers of data, observed chlorophyll *a* interval frequencies for Lake Pepin agree with frequencies predicted from the log normal distribution model.

Citizen interviews

Lake Pepin water-quality conditions were judged unacceptable to lake users in 1988. Respondents to a 1992 interview indicated that once-in-ten-year water quality problems like those that occurred in 1976 and 1988 were unacceptable (Harrison 1992). These two summers were characterized by summer-mean chl *a* concentrations of 52 and 57 µg/L and maxima of 83 and 202 µg/L respectively (Table 3). Also, in early July of 1988 blue-green algae were dominant in samples collected. Over 70 percent of the chl *a* concentrations exceeded 30 µg/L in 1976 and 1988 (Fig. 9). When asked to compare water-quality among years 1991, 1990, and 1988, 52 percent of the 26 respondents indicated that water quality in 1990 and 1991 improved relative to 1988, while 19 percent suggested water quality deteriorated. Summer-mean chl *a* concentrations in 1990 and 1991 were 33 and 31 µg/L, with 45 and 30 percent of the chl *a* concentrations in excess of 30 µg/L (Fig. 9). Blue-green algae were a minor component of the algal populations in June and early July of 1990 and 1991 (Fig. 10).

User perceptions, chlorophyll a, and phytoplankton data

In 1990, CLMP observers on Lake Pepin rated physical condition as "definite algal green" or worse and rated recreational suitability as "swimming impaired" or worse on all dates. Ratings of "no swimming" or "high algal levels and mild odor" were recorded on some dates in July and August. In the upper segment of the lake (Fig. 2), ratings of "no swimming" were noted on August 26 and September 2, when Secchi transparency was 0.6 m. Chl *a* concentrations at a nearby site were 116 µg/L and 58 µg/L on those dates, respectively. Blue-green algae comprised about 30 percent of the algal population (by volume) on those two dates (Fig. 10).

Observers in the lower segment of the lake rated conditions as "swimming impaired" or "no swimming" on several dates in late July and early August. Secchi transparency ranged from 0.3 to 1.35 m and chl *a* ranged from 25 to 75 µg/L during that period. Blue-green algae accounted for 30 to 60 percent of the algal community from mid-July to late August at site UM-171 (Fig. 10).

Lake Pepin Chlorophyll a Goal

When setting water quality goals or criteria it is often appropriate to specify an average (or minimum or maximum) concentration for a specific period of time. Frequently, water quality rules require the standard (goal) to be associated with a flow recurrence

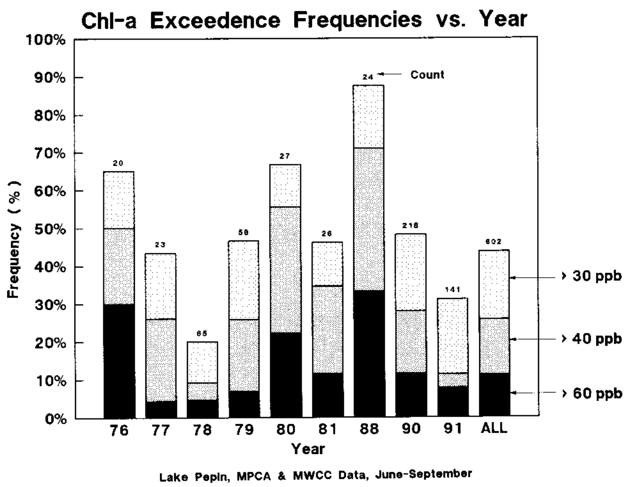

Figure 9.—Chlorophyll *a* exceedance frequencies by year for Lake Pepin.

interval when environmentally critical concentrations may be flow dependent. For example, Minnesota's dissolved oxygen standard requires compliance with the standard 50 percent of the days at which flow is equal to the lowest weekly flow with a once-in-ten year recurrence interval (7Q10; MN Statutes, 1994). In the case of Lake Pepin, TP and river flow combine to produce environmentally critical concentrations of chl *a* and influence phytoplankton composition.

Lake Pepin water-quality data associated with user surveys, citizen interviews, and ecoregion considerations, indicated that chl *a* concentrations

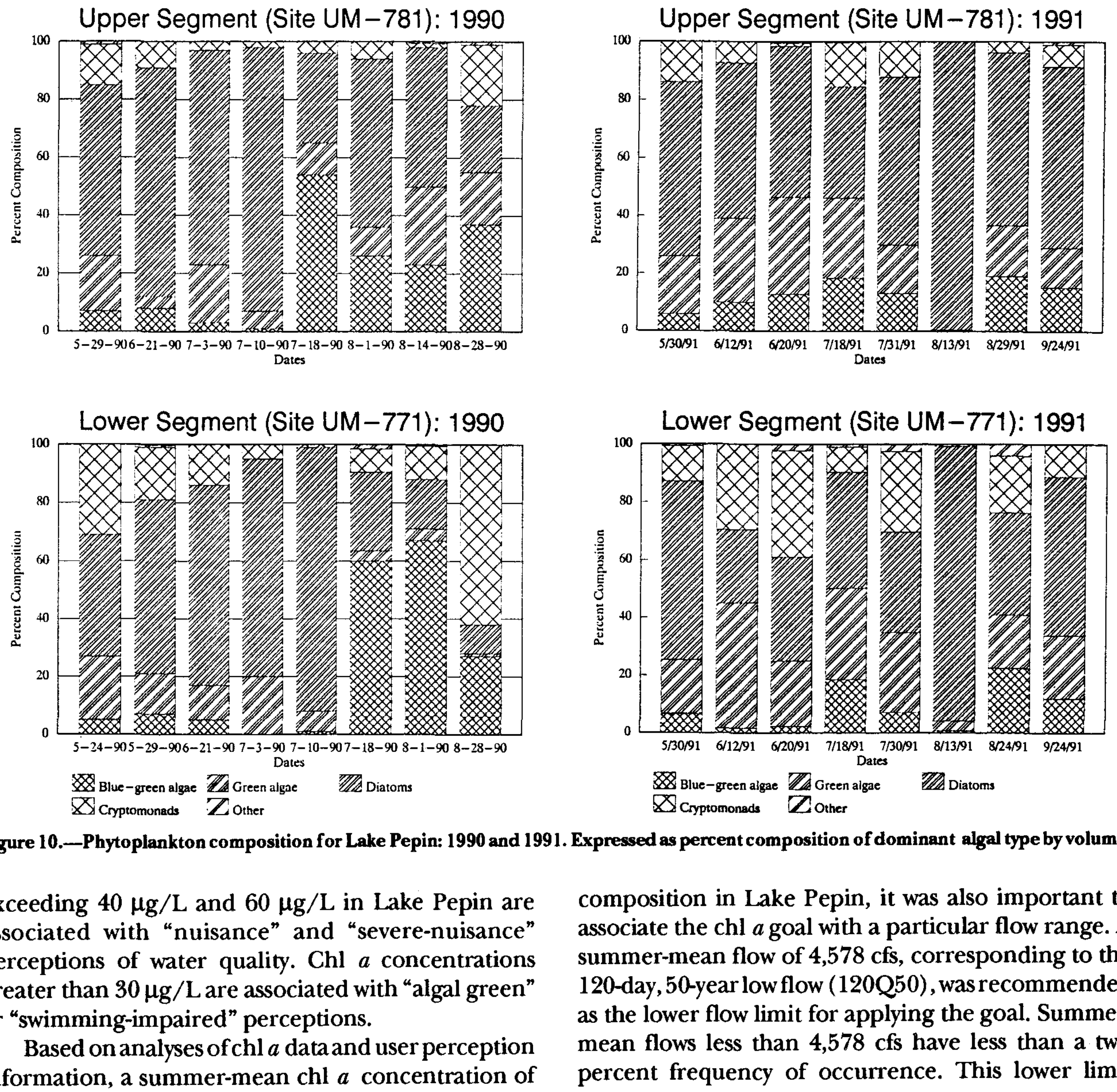

Figure 10.—Phytoplankton composition for Lake Pepin: 1990 and 1991. Expressed as percent composition of dominant algal type by volume.

exceeding 40 μg/L and 60 μg/L in Lake Pepin are associated with "nuisance" and "severe-nuisance" perceptions of water quality. Chl *a* concentrations greater than 30 μg/L are associated with "algal green" or "swimming-impaired" perceptions.

Based on analyses of chl *a* data and user perception information, a summer-mean chl *a* concentration of 30 μg/L was recommended as a water quality goal for Lake Pepin. Though the goal was expressed as a summer-mean the predictive models (Figs. 8 and 9) provided a basis for expressing the mean in terms of percent frequency of nuisance algal conditions over the summer. Achieving this goal will not eliminate concentrations above 30 μg/L, but will limit the frequency of "nuisance algal conditions" (> 40 μg/L) and "severe nuisance conditions" (> 60 μg/L) (Fig. 8).

A slightly higher summer-mean chl *a* goal is not considered appropriate because the frequency of nuisance algal conditions increases rapidly as mean chl *a* increases from 30 to 40 μg/L (Fig. 8). Further, it is appropriate that periods when chl *a* < 30 μg/L, and user-perceived impairment of water quality is minimal, should represent a majority of time during the summer.

Because water residence time partially controls the production of algal biomass and phytoplankton composition in Lake Pepin, it was also important to associate the chl *a* goal with a particular flow range. A summer-mean flow of 4,578 cfs, corresponding to the 120-day, 50-year low flow (120Q50), was recommended as the lower flow limit for applying the goal. Summer-mean flows less than 4,578 cfs have less than a two percent frequency of occurrence. This lower limit

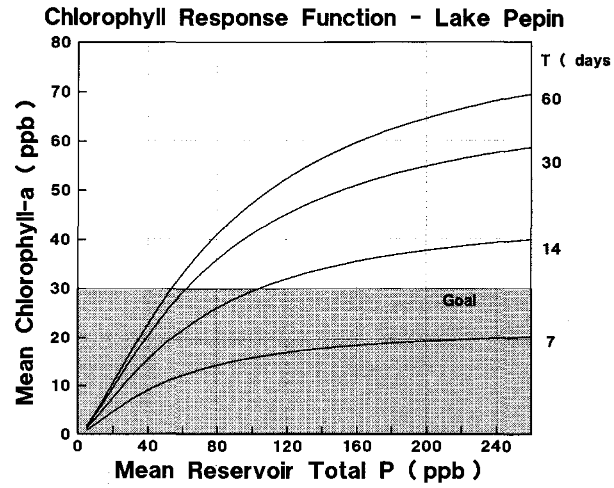

Figure 11.—Chlorophyll response function for Lake Pepin. Expressed as a function of TP concentration and water residence time.

included flows encountered in 1976 and 1988 (Table 3) - two summers characterized as having degraded water quality according to citizen interviews (Harrison 1992). Based on the observed relationship between flow and chl *a* in Lake Pepin (Fig. 6), a control program that is designed to meet the 30 µg/L chl *a* goal at this lower flow limit is likely to protect water quality at higher flows, as well.

A flow of 20,000 cfs was recommended as the upper flow limit for applying the goal. A summer-mean flow of 20,000 cfs provides a residence time of about 11 days, which is within the 10-14 days required for full algal response to available nutrients (Walker 1985b, 1987). An upper flow limit of 20,000 cfs included 1990 - a summer characterized as having impaired water quality. The user perceived impairment in 1990 resulted from high algal concentrations (Fig. 9) and a predominance of blue-green algae in July and August (Fig. 10). In contrast, during the higher flows of 1978, 1979, and 1991 algal concentrations were lower (Fig. 9) and blue-green algae were a small component of the algal population based on 1991 data (Fig. 10).

The generalized modeling network used here (Fig. 3) provided a basis for determining the necessary phosphorus load reductions needed to achieve the chl *a* goal over a range in flow (lake residence time) conditions. Based on our preliminary modeling results, we suggest it will be necessary to achieve an average in-lake TP concentration less than 70 µg/L in order to maintain an average chl *a* concentration less than 30 µg/L in Lake Pepin under 1988 flow conditions (45 day retention time, Fig. 11). An empirical phosphorus retention model calibrated to cross-sectional reservoir data (BATHTUB Phosphorus Model 2: Walker 1987) indicated that an average inflow TP concentration of about 130 µg/L will be necessary in order to achieve an inlake concentration of 70 µg/L under 1988 flow conditions. Based on data collected at Lock and Dam 3, however, the observed average inflow concentration was 250 µg/L in 1988, when the outflow TP concentration (410 µg/L) exceeded the average inflow concentration. This finding indicated that Lake Pepin exhibited an unusually high degree of internal phosphorus recycling in summers with low flow. Achieving an acceptable in-lake phosphorus concentration will require substantial reductions in external (including Metro WWTF and nonpoint sources) and internal phosphorus sources. A linkage between the external and internal sources is felt to exist, but the relationship remains to be quantified.

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