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Design and Evaluation of Eutrophication Control Measures for the St. Paul Water Supply

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ABSTRACT

In 1984, intensive lake and watershed studies were undertaken by St. Paul Water Utility to identify causes and remedies for taste-and-odor episodes that had plagued the supply in recent years. Water is derived from the Vadnais Lake Chain, and fed mainly by diversions from the Mississippi River and runoff from local watersheds. Early phases of the study implicated algal blooms in the storage lakes as the immediate cause of the taste-and-odor problems. Historical control schemes, including routine copper sulfate applications and dosing of various chemicals at the water treatment plant, had been largely unsuccessful. Following three years of collecting baseline data control measures were implemented to address the basic problem of nutrient enrichment. These controls targeted sources of phosphorus including diversions from the Mississippi River, runoff from urban watersheds, and recycling from lake bottom sediments. Specific control measures included: (1) selecting supply sources based upon chemical factors—phosphorus, silica, iron; (2) injecting iron chloride to inactivate orthophosphorus in waters pumped from the Mississippi River; (3) using wet detention ponds to reduce phosphorus loadings in runoff from urban watersheds; (4) aerating the hypolimnion—plus iron chloride injections in 1988. This paper discusses the design and evaluation of control measures and observed lake responses over the 1984-88 monitoring period. Results indicate substantial progress has been made toward reducing nutrient enrichment levels in the supply lakes as well as undesirable impacts on the water supply; these include taste-and-odor, trihalomethanes, and water treatment costs. The ongoing monitoring program will track lake responses and control (success) over a wider range of hydrologic conditions.

Introduction

Nutrient enrichment can interfere significantly with lakes and reservoirs used for water supply purposes (Fig. 1). Water supply problems commonly linked with water source eutrophication include taste-and-odor, chlorinated organics, increased chemical costs, and treatment process disturbances (Bernhardt, 1980a; Walker, 1983; Palstrom et al. 1988). Attempts to solve these problems within the treatment plant can be costly and seldom succeed completely. Targeting sources and cycling of nutrients in water supply lakes and their watersheds is a fundamental approach that can be used in combination with water treatment measures to reduce eutrophication impacts on water supplies. This paper describes eutrophication control measures implemented in St. Paul. Results were derived from an ongoing lake and watershed study initiated in 1984 to identify causes and solutions for taste-and-odor problems (Walker, 1985a, 1986, 1987b, 1988). The control techniques may be applicable to other lakes used for water supply or other purposes.

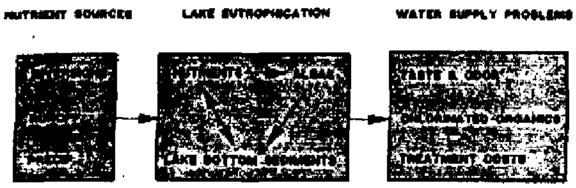

Figure 1.—Cause-effect pathways.

St. Paul Supply System

The St. Paul Water Utility withdraws an average of 1.9 x 10^5 m^3/day from the epilimnion of Vadnais Lake (surface area = 155 hectares, mean depth = 8.1 meters, maximum depth = 16.5 meters). Vadnais is part of a system of 12 interconnected lakes with a drainage area of 6,277 ha located northeast of the city (Fig. 2). The Utility's water intake is the only functional outlet from the lake chain. Based upon hydrologic data for the 1978-84 period, major flow sources include: diversions from the Mississippi River (66 percent), diversions from Centerville Lake/ Rice Creek (18 percent), local watershed runoff (10 percent), and direct precipitation on lake surfaces (6 percent). The hydraulic residence time of the main lake chain (averaging 140 days for Pleasant-Sucker-Vadnais) is essentially determined by the Utility's pumping and withdrawal rates, which reflect consumer demand. The Utility throttles back on Mississippi River and Rice Creek diversions during high runoff periods from the local watershed. Lake levels fluctuate relatively little. Water treatment includes softening, filtration, and disinfection.

Severe taste-and-odor episodes were experienced at increasing frequencies during the late 1970s and early 1980s. The problem appeared related to algal blooms in the supply lakes (Fig. 3). Attempts to control these episodes by adding chemicals at the water treatment plant (principally powdered carbon and potassium permanganate) and applying copper sulfate to the supply lakes every week during the growing season were largely unsuccessful. Periods of fishy (generally in late spring or early summer) and musty (generally in late summer or early fall) water prompted consumer complaints. An intensive study was initiated in 1984 to identify problem sources and possible solutions.

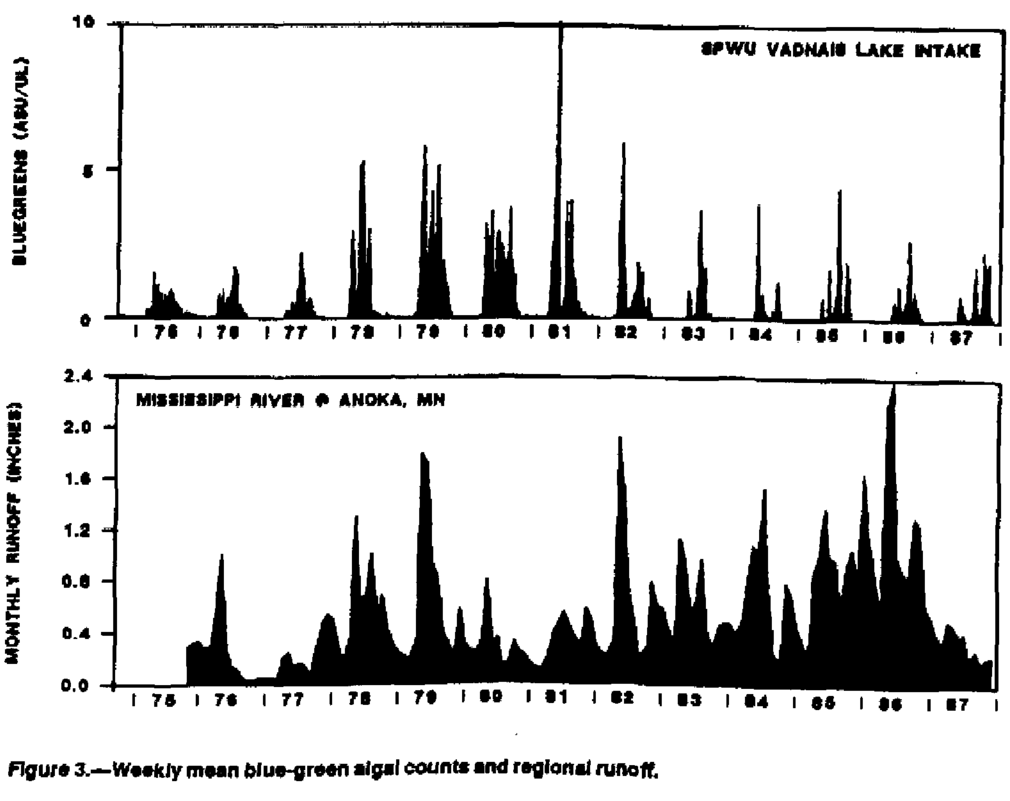

Figure 3.—Weekly mean blue-green algal counts and regional runoff.

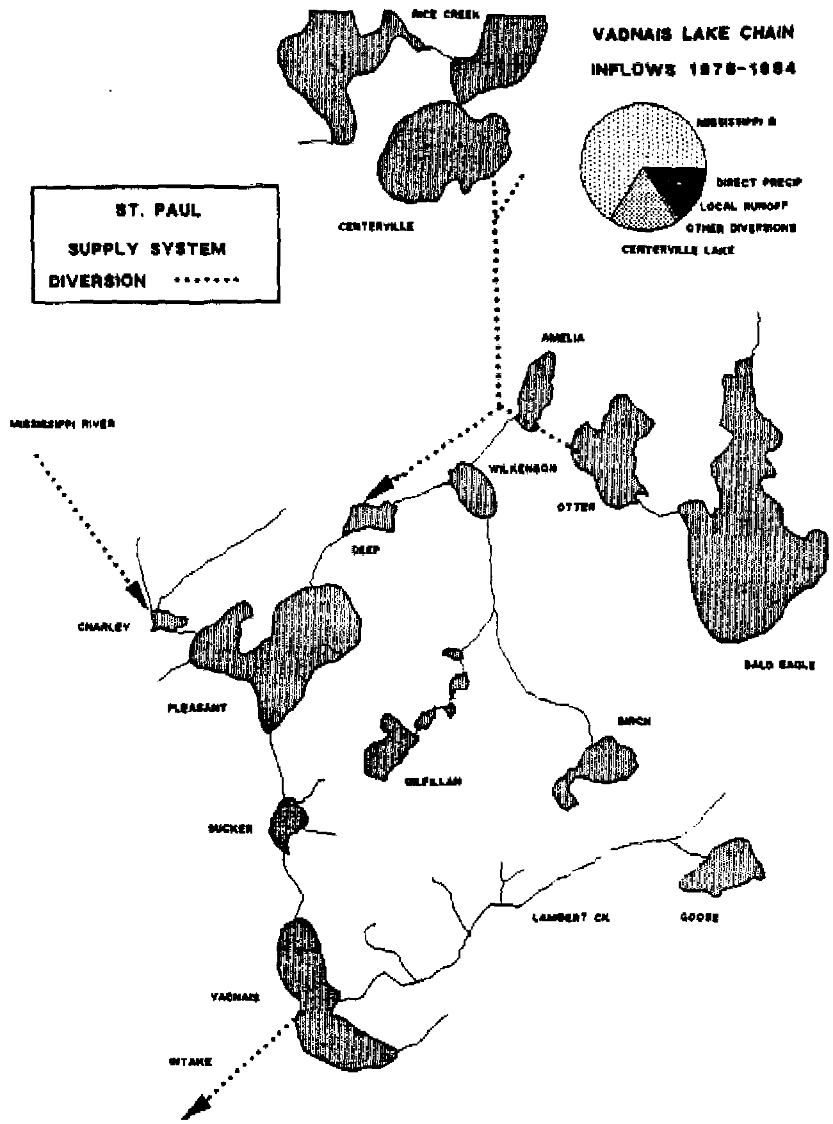

Figure 2.—St. Paul supply system.

chlorophyll a, and threshold odor numbers were also monitored daily at the Utility's water intake in Vadnais Lake.

Direct statistical relationships between measures of lake algal density (counts, chlorophyll a) and threshold odor numbers are difficult to establish because of the highly variable nature of lake algal populations, the importance of algal type, the importance of other organisms (e.g., actinomycetes) that may increase in number following algal blooms and produce taste-and-odor compounds (Gerber and Lechevalier, 1965; Bratzel et al. 1977), and the limitations of measuring the threshold odor number. Similarly, the intake threshold odor number does not directly measure the risk of a taste-and-odor episode in the distribution system because some taste-and-odor compounds are more easily treated than others. Despite this variability, analysis of 1975-84 data (Walker, 1985b) revealed the three most severe taste-and-odor episodes on record occurred in June of 1979, 1981, and 1984, and were accompanied by blue-green algal counts exceeding 5,000 asu/ml. Other, less severe episodes experienced during midsummer and turnover periods typically were accompanied or preceded by blue-green pulses. Important blue-green types included *Anabaena* and especially *Aphanizomenon*.

Because compounds responsible for taste-and-odor are extremely potent and water is stored in the distribution system, blooms of relatively short duration (1-2 days) often triggered episodes and consumer complaints lasting a week or more. This illustrates it is important to conduct high-frequency monitoring in supply lakes, if monitoring information is to be used in "real time" to guide treatment operations. Even with high-frequency monitoring, the ability to control the problem using chemical dosing or other treatment process adjustments is limited without major capital investments.

Monitoring Program

A network of monitoring stations was established in 1984 to develop baseline data for diagnostic purposes and to track lake and watershed responses to control measures implemented in and after 1985. The ongoing monitoring program involves 9 lake profile stations; 32 tributary, diversion, or lake outflow stations; and 8 watershed runoff stations equipped for continuous flow gauging and automatic sampling during storm events. Lake and outflow stations were sampled at frequencies ranging from weekly to monthly over the 1984-88 period. Algal counts, Monitoring data from 1984 indicated algal growth in the supply lakes was limited by phosphorus, nitrogen, and/or silica, depending upon season and lake (Walker, 1985b). Epilimnetic total phosphorus and chlorophyll *a* concentrations in Vadnais Lake during the summer of 1984 averaged 47 ppb and 19 ppb, respectively, indicating highly eutrophic conditions. Mixing of phosphorus-rich waters from eroding lake thermoclines in early fall increased mixed-layer phosphorus concentrations in Pleasant, Sucker, and Vadnais Lakes to 100-200 ppb.

Modeling studies (Walker, 1985a) indicated summer epilimnetic phosphorus must decrease by 50 percent to reduce the nuisance algal blooms frequency from 14 percent to less than 1 percent. Nuisance algal blooms and high risk of taste-and-odor episodes occurred when chlorophyll *a* concentration exceeded 30 ppb.

To predict algal bloom frequency, a model relating mean chlorophyll *a* to mean nutrient concentrations was linked with a model relating chlorophyll *a* interval frequencies to mean chlorophyll *a*, based upon the lognormal frequency distribution (Walker, 1984, 1985a). Phosphorus balance calculations (Fig. 4) showed the relative importance of loadings from Sucker Lake (2073 kg derived primarily from the Mississippi River); runoff from the local watershed (1303 kg); recycling from lake bottom sediments (around 2500 kg); and direct precipitation (34 kg) as sources contributing to the problem.

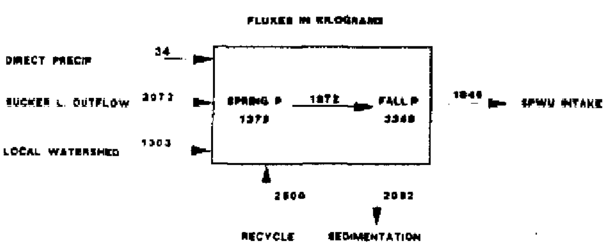

Figure 4.—Vadnais Lake phosphorus balance for April–September 1984. "Recycle" (2500 kg) is assumed to equal the measured increase in phosphorus stored in lake between spring minimum (May) and summer maximum (August). "Sedimentation" is calculated by difference. Other terms are directly measured.

Monitoring from 1984 to 1986, a period of above-average runoff, provided additional information for diagnosing lake conditions and designing control measures. The control program objective described here is to reduce phosphorus sources enough to restore Vadnais Lake to a mesotrophic status—less than 25 ppb, a level more compatible with its use as a water supply. Two important controls (hypolimnetic aeration and iron injection at the Mississippi River intake) were implemented in fall 1986 and spring 1987, respectively. Direct evaluation of lake responses to these controls was hindered by dramatic variations in flow and runoff experienced during the 1984-86 monitoring period. As shown in Figure 3, regional runoff experienced from 1984 to 1986 was much greater than that experienced during 1987.

To some extent, effects of runoff variations on phosphorus loadings to the Vadnais Lake Chain were buffered by the Utility's pumping activity. For example, during drier periods, more flow was pumped from the Mississippi River. Although local watershed runoff was 7.3 times higher in April–September 1986 than April–September 1987, external total phosphorus loading to Vadnais Lake was only 1.8 times higher. Phosphorus releases from lake bottom sediments also tended to reduce hydrologic variability effects on lake algal productivity. Long-term time series (Fig. 3) indicated no systematic relationship between runoff rate and algal counts. It is unlikely the lower blue-green counts observed in Vadnais Lake during 1987-88 were attributable to the drought, since algal counts were much higher during 1980-81, also a period of below-average runoff (Fig. 3).

Results of the 1984-88 monitoring program are summarized in Figures 5 through 9. These figures provide a partial basis for evaluating the control measure effectiveness discussed here. A primary objective of the ongoing monitoring program is to observe lake conditions under a wide range of flow conditions with the control measures in place.

Control Strategies

Control strategies have been designed based upon the cause-effect pathways linking nutrient sources, in-lake nutrient cycling algal blooms, and taste-and-odor episodes (Fig. 10). Because of the lake chain complexity and the lack of a single predominant nutrient source, it was apparent several control techniques would be necessary to achieve program objectives. The four major control techniques used—Source Selection, Source Treatment, Watershed Management, and Hypolimnetic Aeration—are discussed in the following pages.

Source Selection

Source selection refers to preferential supply source pumping sources based upon lake water quality impact considerations. The Mississippi River was the predominant supply source during 1978-84, contributing 66 percent of lake inflows. The Centerville Lake/Rice Creek source was used primarily during

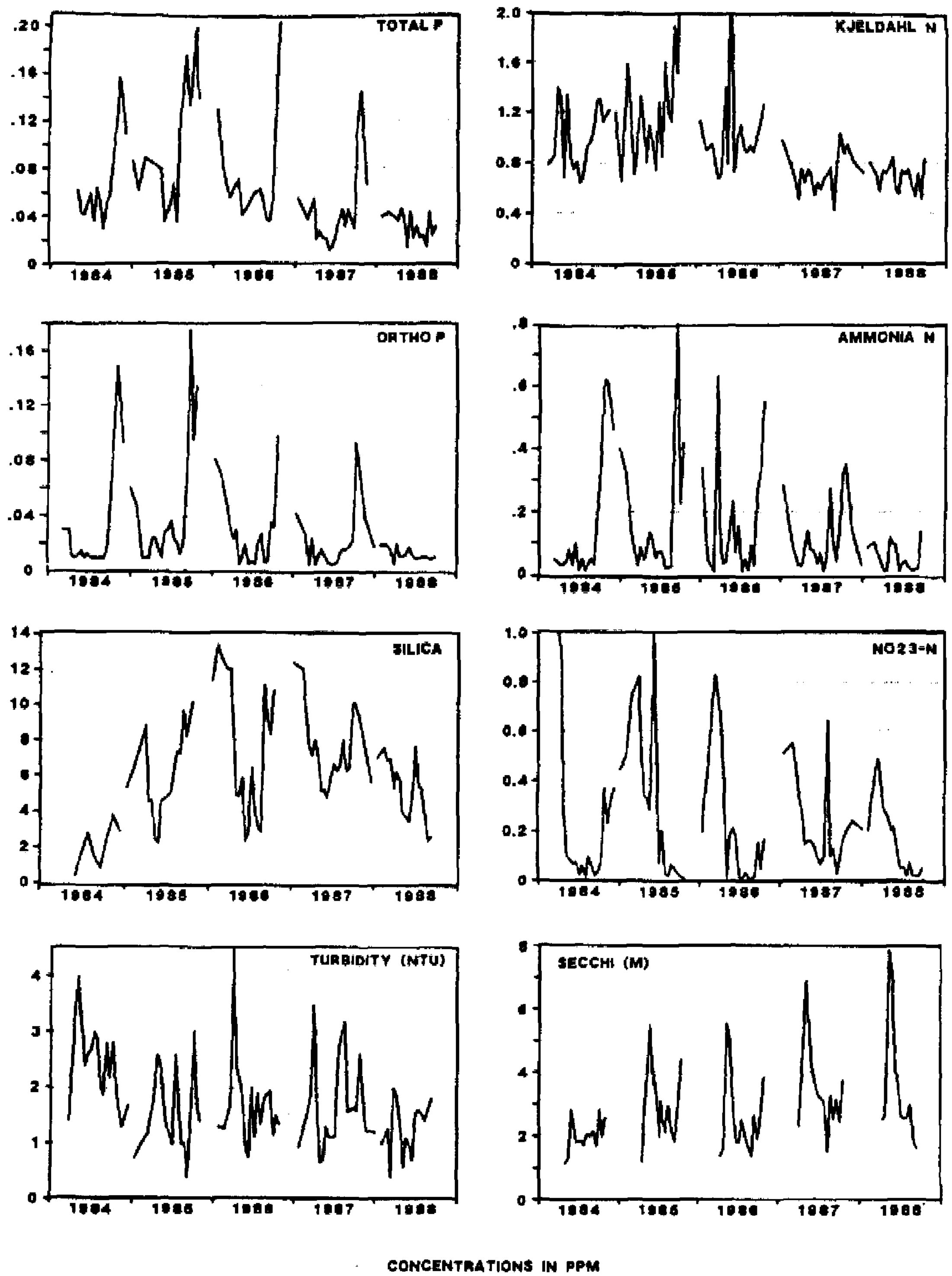

Figure 5.—Vadnais Lake epilimnetic time series.

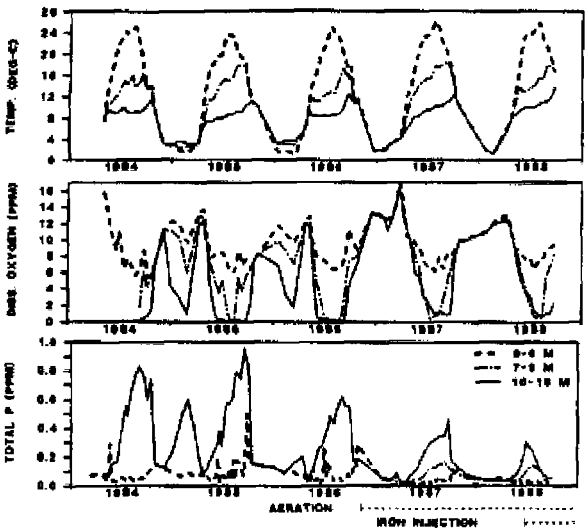

Figure 6.—Vadnais Lake time series by depth interval.

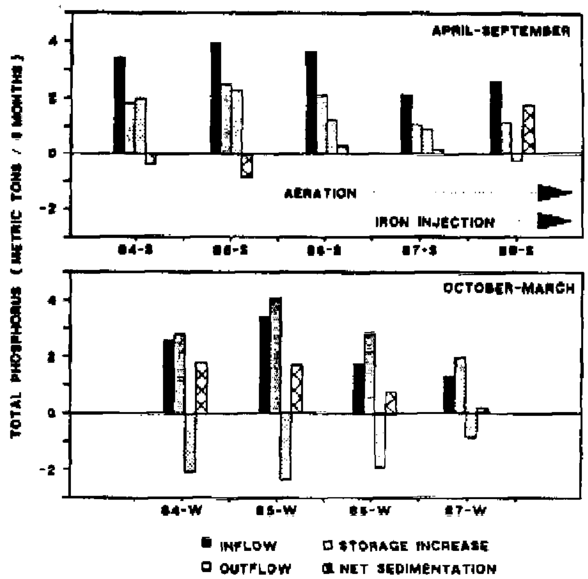

Figure 7.—Vadnais Lake seasonal phosphorus balances. "Storage increase" is calculated from lake profile monitoring data (volume-weighted concentration times lake volume) at the beginning and end of each time period. "Inflow" and "outflow" terms are based upon direct monitoring of inflow streams and SPWU intake. "Net Sedimentation" is calculated by difference; it equals inflow minus outflow minus storage increase.

winter and spring (19 percent of lake inflows). Other sources such as Otter Lake and Centerville Wells were also available, but in limited volume, less than 1 percent of lake inflows.

Suspension of pumping from Rice Creek was recommended after analyzing 1984 monitoring data, considering important nutrient pathways (Fig. 11), and comparing source water quality (Fig. 12). Since total and orthophosphorus concentrations were similar, source selection strategy would not directly affect phosphorus loadings to the lake chain. Silica and iron levels were much lower in Rice Creek, however. This reflected the presence of numerous shallow eutrophic lakes in the Rice Creek watershed. It was hypothesized lower silica and iron levels in the supply

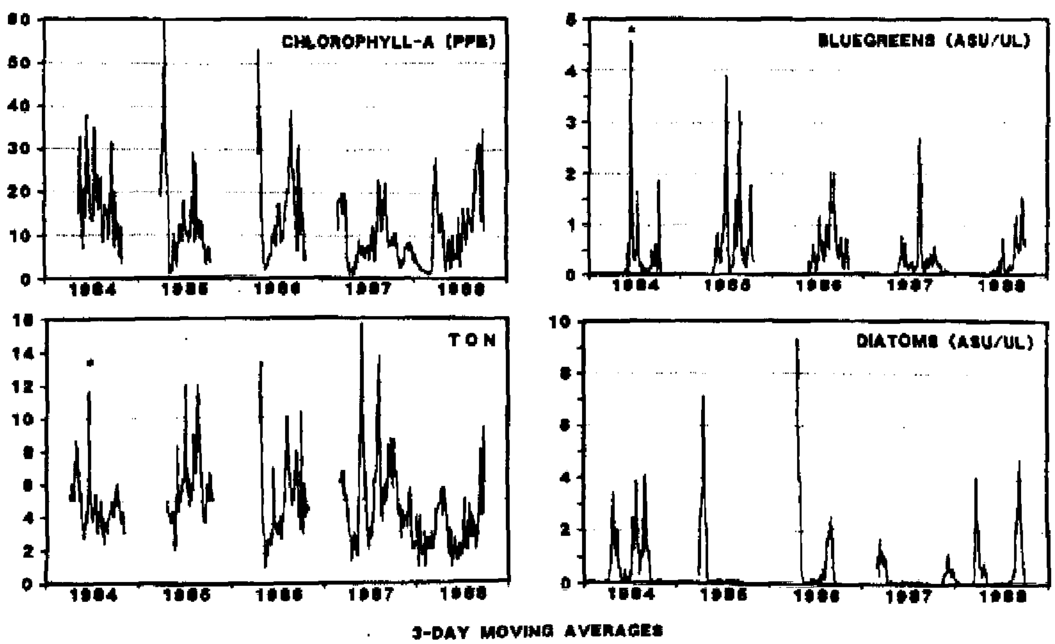

Figure 8.—Vadnais intake algal counts.

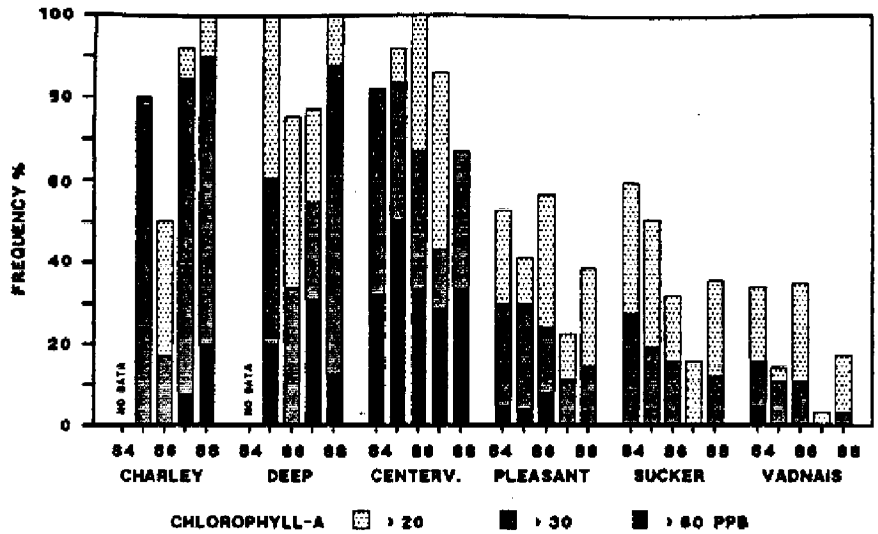

Figure 9.—Algal nuisance frequencies by lake and year.

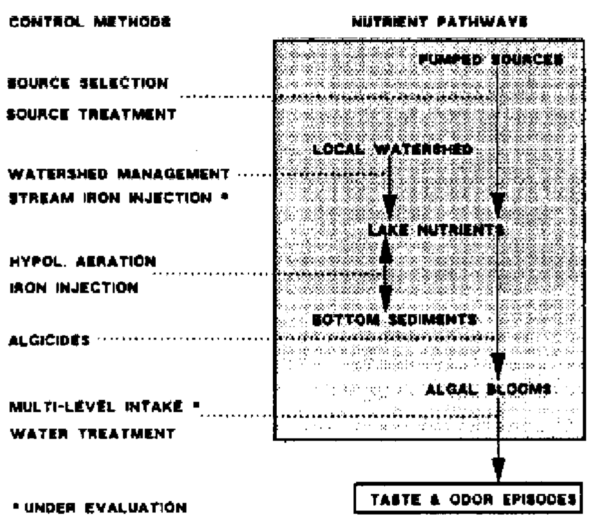

Figure 10.—Taste-and-odor control strategy.

source would promote blue-green algal productivity, as opposed to less damaging phosphorus pathways leading to lake bottom sediments or diatom productivity.

Water sources with higher silica levels were preferred to avoid depleting silica from the Vadnais Lake Chain. In May 1984, after a winter of intensive pumping from Centerville Lake, silica was depleted in Vadnais (Fig. 5), as well as other lakes in the chain. Limiting silica for spring diatom growth left more phosphorus to support summer blue-green populations. Theoretically, using available silica-rich sources would increase spring diatom growth but decrease summer blue-greens, the primary concern from a taste-and-odor perspective.

Higher iron levels increase the phosphorus retention capacity of lake sediments. Hypolimnetic iron/phosphorus ratios in Pleasant and Vadnais Lakes were less than .5 in August 1984. Ratios exceeding 3 are desired to promote iron phosphate precipitation during lake turnover periods (Stauffer, 1981). Significant increases in mixed-layer phosphorus and chlorophyll *a* concentrations were observed during thermocline erosion periods in late August 1984 and subsequent years. Based upon lake sediment survey results (Engstrom, 1986) and the observed depletion of sulfate from Pleasant and Vadnais lakes' hypolimnia during summer 1984, insoluble iron sulfide

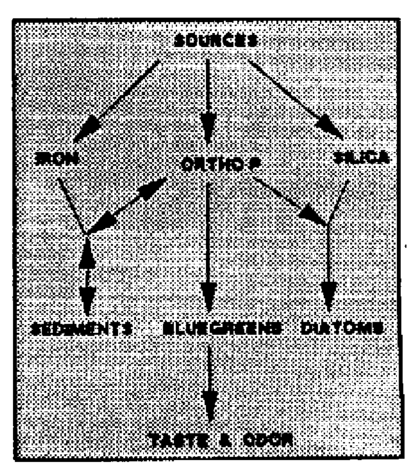

Figure 11.—Nutrient pathways.

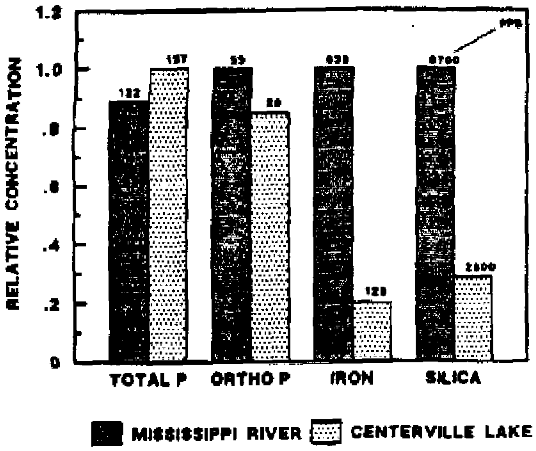

Figure 12.—SPWU source comparisons.

production was a major factor contributing to iron deficiency. Iron is also an important factor regulating phosphorus releases from shallow lake sediments (Ripl, 1986). Use of an iron-poor source such as Centerville Lake would promote iron deficiency and phosphorus recycling from lake sediments. Using Mississippi River water, particularly in combination with iron injection and hypolimnetic aeration, would promote iron enrichment and phosphorus retention in lake sediments.

Based on these hypotheses, pumping from Centerville Lake was suspended in fall 1984. The Mississippi River was pumped exclusively until July of 1988 when an extreme drought forced the Utility to pump from Centerville Lake for a period of approximately three weeks. Higher silica levels were observed in all lakes during 1985-88 and silica-limited conditions were avoided (Fig. 5). In Vadnais Lake, peak diatom counts in spring 1985 and 1986 were approximately twice those observed in 1984 (Fig. 8), but did not trigger a taste-and-odor episode. Peak bluegreen populations in Vadnais Lake decreased each year following 1984. Phosphorus accumulation in the Vadnais Lake hypolimnion also decreased between 1984 and 1986. Although it is impossible to prove these changes resulted from the new source pumping strategy, the observations were consistent with the hypotheses and in a favorable direction.

Source Treatment

Source treatment refers to adding or removing chemicals from pumped diversions to reduce lake impacts. Several alternatives were considered, primarily with respect to the Mississippi River source. Obviously, it would be desirable, although costly, to remove phosphorus via physical/chemical treatment, as demonstrated by Bernhardt (1980b) at Wahnbach Reservoir, Germany. While not ruled out, a less extreme and less costly alternative—phosphate deactivation by iron chloride injection—was implemented on a trial basis in the spring of 1987. This technique had successfully reduced algal growth in water supply systems with river pumping and lake storage components in England (Hayes et al. 1984) and the Netherlands (Bannink and VanDer Vlugt, 1978).

Phosphate ions adsorb to insoluble ferric hydroxides formed when iron chloride solution is injected into water pumped from the river. Although reversible, this process renders orthophosphorus less available to stimulate algal growth in the downstream lakes. Factors such as pH, mixing, temperature, and oxidation-reduction potential can influence the process (Lijklema, 1980). Aluminum sulfate can also be used for this purpose and is less susceptible to phosphate release under low-redox conditions. Alum used in place of iron chloride in this case would require much higher doses (greater than 10 ppm aluminum versus approximately .5-1 ppm iron) because of high alkalinity (approximately 150 ppm). Toxicity risks would also be higher for alum than iron. Based upon average concentrations in the Mississippi River (total phosphorus = 122 ppb, orthophosphorus = 33 ppb, Fig. 12), iron treatment to reduce orthophosphorus concentrations below 10 ppb would remove 70 percent of the orthophosphorus load from the river. Subsequent sedimentation of the insoluble iron-phosphate complexes would remove 19 percent of the total phosphorus load. The process' success would depend upon the reversibility of the iron/phosphate reactions in the downstream lake environments. These reactions could be evaluated using a full-scale experimental approach.

Laboratory and field-scale tests evaluated dose-removal relationships in samples taken from the Mississippi River and other locations in the Vadnais Lake chain (Walker, 1987b). Results showed removal ratios—orthophosphorus removed to iron added—ranged from .01 to .28. A full-scale field test was conducted in July 1986 (Fig. 13). Iron chloride, a liquid approximately 13 percent iron by weight, was injected into the water pumped from the river. The flow passed through 15 km of underground conduits and through Charley Lake (a shallow, 12-ha lake with a hydraulic detention time of approximately one day) into Pleasant Lake. Five week-long dose levels (0, .5, 1, 2, and 0 ppm iron) were tested. Phosphorus, iron, and other water quality measurements were collected twice daily at three locations: the river (before injection), the conduit outlet, and Charley Lake outlet.

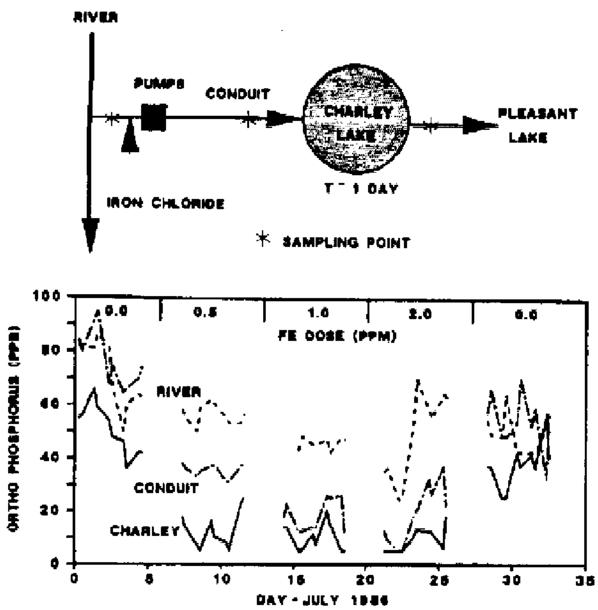

Figure 13.—Iron chloride injection test.

Orthophosphorus time series at each station are shown in Figure 13. Results indicated orthophosphorus levels declined significantly in the conduit and lake outflow following injection of iron chloride. At the lowest non-zero dose tested (.5 ppm iron), the average orthophosphorus level at the lake outflow station decreased from 45 to 13 ppb. Since higher doses did not significantly improve reductions, the .5 ppm dose was recommended for full-scale implementation. Most of the injected iron was removed by sedimentation in Charley Lake.

Iron chloride has been injected at the St. Paul Water Utility Mississippi River pumping station since April 1987. Evaluating impacts on the Vadnais Lake chain was difficult because significant reductions occurred in Mississippi River flow and phosphorus during the 1987-88 drought. Average orthophosphorus levels in the river dropped from 38-44 ppb in 1984-86 (wet years) to 18 ppb in 1987 and 1988 (dry years). This drop reflected less runoff, lower flow velocities, and increased algal growth in the Mississippi River during dry periods. Although Pleasant Lake phosphorus concentrations, blue-green algal densities, and algal nuisance frequencies (Fig. 9) were lower in 1987-88 than 1984-86, monitoring over a longer time frame is required to evaluate iron injection impacts on Pleasant Lake and other lakes in the Vadnais Chain.

Watershed Management

Monitoring stations in the local watershed revealed five- to ten-fold higher rates of runoff and phosphorus export from urban versus undeveloped watersheds in the lake chain (Walker, 1985a, b). Significant urban growth was, and is, occurring in the local watershed, particularly along Lambert Creek, which discharges directly into Vadnais Lake. Mass-balance modeling (Walker, 1985a) indicated projected full development of the watershed would increase Vadnais Lake total phosphorus concentrations from 47 to 59 ppb, and the frequency intake chlorophyll *a* concentrations exceeding 30 ppb would rise from 14 to 26 percent. This situation identified a need to reduce existing and future urban development impacts to control taste and odor and other undesirable effects of eutrophication. The watershed management program described here is not expected to provide immediate benefits, but is an investment critical to long-term protection of Vadnais Lake and its use as a water supply.

To address future development impacts, the Utility worked with local communities to develop a Watershed Management Plan (Vadnais Lake Area Water Manage. Organ. 1986). The plan included watershed resources inventories, designated existing and future land uses, and specified management practices to reduce urban runoff to the lakes. Derived primarily from the U.S. Environmental Protection Agency's Nationwide Urban Runoff Program, design criteria for detention ponds were incorporated into the plan (Walker, 1987a). Wet detention ponds or equivalent controls are now required in all new watershed developments and are expected to reduce phosphorus from such developments by approximately 55 to 65 percent.

The feasibility of constructing detention ponds at various locations along Lambert Creek mainstem (Fig. 2) is being evaluated to address the impacts of runoff from existing urban areas. These ponds would trap sediment and phosphorus, and reduce streambed erosion, a significant phosphorus source in some sections of the creek.

Hypolimnetic Aeration

Profile monitoring revealed significant oxygen depletion and phosphorus accumulation in Vadnais Lake hypolimnion during winter and summer stratified periods from 1984 to 1986 (Fig. 6). Seasonal mass balances (Fig. 7) showed net phosphorus sedimentation during summer stratified periods was near zero. Soluble phosphorus movement from the hypolimnion and thermocline into the epilimnion significantly increased algal bloom potential during late summer (period of thermocline erosion), the fall turnover, and spring turnover. Because of the iron deficiency explained earlier, recycled phosphorus was not checked by iron phosphate precipitation.

Hypolimnetic aeration can effectively reduce phosphorus accumulation in lake bottom waters (Bernhardt, 1975; Smith et al. 1975; Fast and Lorenzen, 1976; Pastorok et al. 1981). Two hypolimnetic aeration units ("LIMNOs" furnished by Aqua Technique, Inc.) were installed in Vadnais Lake in November 1986. Aeration was introduced to maintain an aerobic sediment–water interface throughout the year and reduce the portion of the phosphorus recycling contributed by low redox conditions. This would reduce the surface nutrient supply during thermocline erosion and lake turnover periods.

Figure 6 shows variations in temperature, dissolved oxygen, and total phosphorus by depth interval over the 1984-88 monitoring period. The aerators maintained average hypolimnetic oxygen concentrations above .8 ppm during the summers of 1987 and 1988. Before aeration, the hypolimnion was anaerobic from mid-June through mid-September. Horizontal distribution of aeration was generally good, based upon profile monitoring at the northern and southern extremities of the hypolimnetic basin—525 meters from the aerators. Profiles taken on July 5, 1988 (Fig. 14) showed 10-16 deep oxygen hypolimnetic concentrations decreasing from 3-4 ppm in the immediate vicinities of the north and south stations to 2-3.5 ppm at the north, central, and south end stations. Consistent with observations by Taggart (1984) and McQueen and Lean (1986), the aerators had limited influence on oxygen concentrations in the thermocline (7-9 meters), where distinct oxygen minima were observed at all stations.

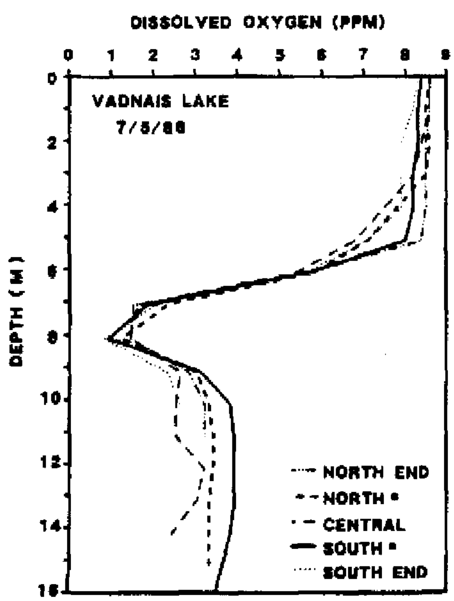

Figure 14.—Oxygen profiles - July 5, 1988.

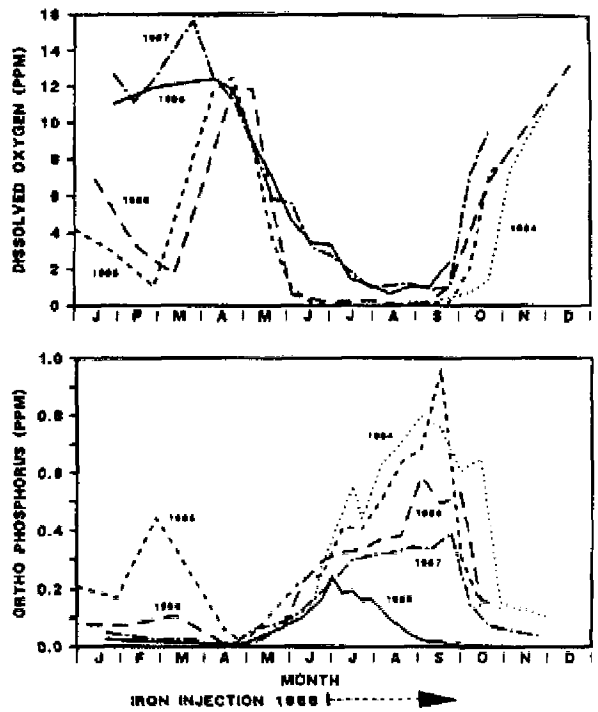

Figure 15.—Seasonal variations in dissolved oxygen and orthophosphorus Vadnais Lake hypolimnion 1984-88.

Hypolimnetic responses to aeration included reduced ammonia and Kjeldahl nitrogen levels and increased nitrate and sulfate levels. Seasonal variations in hypolimnetic dissolved oxygen and orthophosphorus concentrations are plotted in Figure 15. One effect of aeration was eliminating thermal stratification (Fig. 6) and hypolimnetic dissolved oxygen loss during winter. Orthophosphorus accumulation in the hypolimnion under ice cover was also eliminated, based upon a comparison of orthophosphorus levels in March 1985 and 1986 (.1-.5 ppm) with levels in March 1987 and 1988 (less than .04 ppm). These reductions were important because they influenced the orthophosphorus supply at spring turnover. As indicated in Figure 8, maximum spring diatom counts and chlorophyll a levels were also lower in 1987 and 1988, compared with 1986 and 1987; silica limited peak diatom levels in spring 1984.

Beneficial hypolimnetic aeration impacts on phosphorus cycling depend upon iron availability (Lean et al. 1986; McQueen and Lean, 1986). As discussed earlier, both the hypolimnion and bottom sediments of Vadnais Lake were deficient in iron for phosphorus control. Seasonal mass balances indicated aeration alone had little influence on net phosphorus sedimentation from April through September 1987 (Fig. 7). Although total phosphorus concentrations in the epilimnion (Fig. 5) and hypolimnion (Fig. 6) were lower in 1987 than previous years, these decreases may have been related more to lower runoff and reduced external loadings during 1987 than to aeration effects.

Experiments conducted during the summer of 1988 indicated injecting iron chloride into the aerators could significantly decrease hypolimnetic phosphorus accumulations and increase lake sediment phosphorus retention. Iron chloride was injected continuously at the base of the aerators, just above the air diffuser rings, from June 30 through October 1, 1988. Measured phosphorus accumulation rates in the hypolimnion ranged from 7 kg/day (May-August 1987) to 17 kg/day (May-August 1985). For this accumulation range, the iron injection rate selected for the full-scale experiment (100 kg iron/day) corresponded to a removal ratio of .07 to .17 g orthophosphorus/g iron, consistent with results of laboratory dosing experiments using hypolimnetic waters (.10-.28 g phosphorus/g iron) and with the .10 g. phosphorus/g iron removal ratio reported by Lean et al. (1986) for a similar full-scale experiment.

As shown in Figure 15 hypolimnion orthophosphorus accumulation was reversed when iron injection began at the end of June 1988. Good horizontal distribution was observed, based upon profile monitoring at the northern and southern extremities of the hypolimnetic basin. During the first four weeks of the experiment, the entire 100 kg/day dose was injected into the south station aerator. During the next two weeks the dose was injected into the north unit. During the last six weeks the dose was alternated daily between the south and north aerator stations. Hypolimnetic phosphorus measurements in each lake region showed rapid response to iron injection (Fig. 16). Considerable horizontal transport within the hypolimnion was indicated by decreasing orthophosphorus concentrations in the northern lake during July, when iron was injected only at the south unit. The steady increase of orthophosphorus at 8 m during dosing periods suggested limited penetration into the thermocline. Apparently iron dosing in combination with hypolimnetic aeration substantially reduced the ortho- and total phosphorus concentrations at fall turnover in 1988 to 35 ppb (versus 100-200 ppb for previous years) (Fig. 5). Net sedimentation of phosphorus during April through September ranged from -854 to 281 kg in 1984-1987, to 1763 kg in 1988 (Fig. 7).

Despite substantial hypolimnetic phosphorus reductions attributed to the iron treatment, algal blooms developed in late August and early September 1988, when chlorophyll a exceeded 30 ppb (Fig. 9). The intake threshold odor number also increased to 9 units during this period, but a taste-and-odor episode did not occur. These algal blooms coincided with erosion of the thermocline in late August. Most of the metalimnetic phosphorus accumulated prior to iron injection at the end of June. Starting iron injection earlier in the season when the thermocline is higher

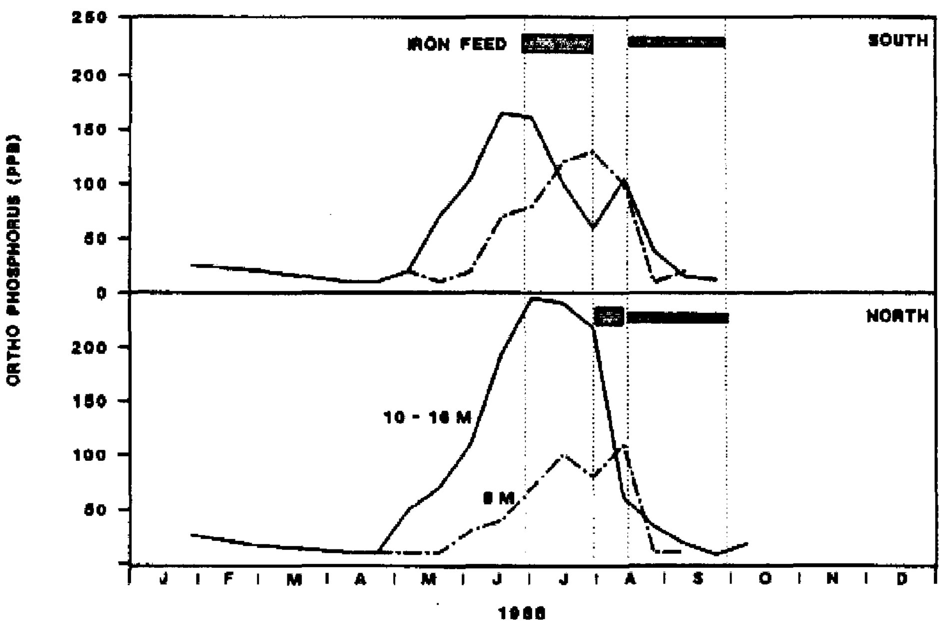

Figure 16.—Orthophosphorus responses to iron chloride injection in northern and southern lake regions.

(early May versus late June) may help to reduce metalimnetic buildup of orthophosphorus and the risk of algal blooms during late summer.

One remaining uncertainty concerns the extent iron treatment will penetrate the thermocline. Another uncertainty is treatment longevity. Based upon sedimentation rates estimated via Pb-210 dating (Engstrom, 1986) the total mass of iron injected during 1988 (approximately 9,200 kg) equaled 130 to 210 percent of the existing iron sedimentation rate, or 41 percent of all the iron stored in the top 2 centimeters of lake bottom sediment before treatment. Ideally, iron injection continued over a few seasons combined with reduced algal productivity and efficient aeration would replenish the bottom sediment iron content and provide long-term benefits. This would reduce the need for continuous iron injection, provided aerobic conditions are maintained. Some of the phosphorus intercepted by the iron treatment may be unrelated to bottom sediment conditions; for example, phosphorus released from decaying seston, particularly after the spring diatom bloom. Intercepting this phosphorus may require long-term iron injection. This technique's success also depends upon the horizontal pattern of iron deposition around the aerators, which has not yet been evaluated. Gradual oxidation of the sediments under aerobic conditions may have beneficial effects on phosphorus cycling detectable only over long time periods. The short-term strategy is to continue with the iron injections during the summer stratified period until more is learned about lake responses.

Other Control Measures

Several other control techniques are being evaluated (Fig. 10). Hypolimnetic aeration has been recommended for Pleasant Lake to reduce phosphorus transport from the upper lake chain (Walker, 1988). A multi-level intake structure for Vadnais Lake for use of hypolimnetic or metalimnetic waters during surface algal blooms is being investigated (Owens, 1988). In the local watershed, preliminary designs for regional detention basins on Lambert Creek mainstem (Fig. 2) have been developed. Iron chloride injection at the mouth of Lambert Creek will be tested in 1989. Finally, curtailing or suspending copper sulfate treatments in favor of the nutrient-based control strategies outlined here is being considered. Continued watershed and lake chain monitoring will provide a basis for evaluating and refining the control techniques under a wider range of hydrologic conditions.

Related Impacts

Observed lake responses over the 1984-88 period suggest progress was made toward achieving a mesotrophic status for Vadnais Lake and reducing the risk of taste-and-odor episodes. As suggested by Figure 1, reductions in algal productivity should have beneficial impacts on chlorinated hydrocarbons and treatment costs. Treated-water trihalomethane (THM) concentrations and chemical costs for 1984-88 are shown in Figure 17.

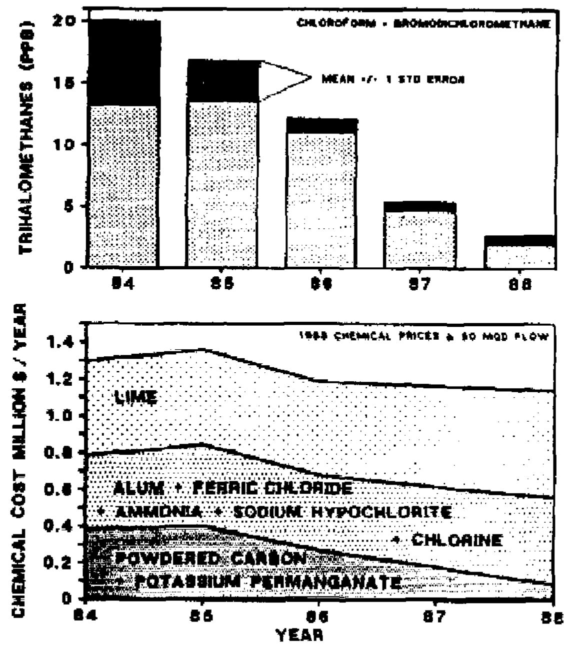

Figure 17.—Treated-water trihalomethanes and total chemical costs 1984-88.

Chemical costs were computed from daily doses and normalized to 1988 chemical prices and an average flow of 1.9×10^5 m^3/day (50 mgd). Chemicals were divided into three categories based upon probable sensitivity to source eutrophication. Powdered carbon and potassium permanganate costs (used exclusively for taste-and-odor control) should be relatively sensitive to source eutrophication, while the costs of lime (used for softening) should be relatively insensitive.

Reduced trihalomethane levels and chemical costs are consistent with improved lake water quality, although other factors may be involved. For example, lower trihalomethane levels in 1987 and 1988 may be partly related to the application of chlorine dioxide, a change in the water treatment process. Cost savings attributed to reductions in potassium permanganate and powdered carbon doses were $300,000/year between 1984 and 1988. Net economic impacts should be evaluated over a longer period of record and consider eutrophication control costs. A strictly economic evaluation of the program is infeasible, however, because the benefits of reducing the frequency and severity of taste-and-odor episodes and lower trihalomethane levels cannot be expressed in terms of dollars.

Conclusions

Observed responses in the lakes and water treatment plant suggest that the nutrient-based control strategy (Fig. 10) was effective in reducing: (1) algal growth in the water supply lakes, (2) the risk of taste-and-odor episodes, and (3) other undesirable impacts of eutrophication on the water supply. This progress was facilitated by the Utility's commitment to intensive monitoring and the whole-lake experimental programs described. Additional studies are required to evaluate lake responses under a wider range of hydrologic conditions, to refine the control measures, and to quantify long-term benefits.

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