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NUTRIENT-BASED CONTROL STRATEGIES FOR TASTE-AND-ODOR

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INTRODUCTION

Nutrient enrichment can interfere significantly with lake and reservoir uses for water-supply purposes (Figure 1). Water-supply problems commonly linked to source eutrophication include taste-and-odor, chlorinated organics, increased chemical costs, and treatment process disturbances (1,2,3). Attempts to solve these problems within the treatment plant can be costly and are seldom completely successful. Targeting the sources and cycling of nutrients in the supply lakes and their watersheds is a fundamental approach which can be used in combination with water treatment measures to reduce eutrophication impacts on water supplies. This paper describes eutrophication control measures which have been implemented in St. Paul. Results are derived from an ongoing lake and watershed study which was initiated in 1984 to identify causes of and solutions for taste-and-odor problems (4,5,6,7,8). The control techniques may applicable to other lakes used for water supply and/or other purposes.

ST. PAUL SUPPLY SYSTEM

The St. Paul Water Utility withdraws an average of .19 x 10^6 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 hectares located northeast of the city (Figure 2). The Utility's water intake is the only functional outlet from the lake chain. Based upon hydrologic data for the 1978-1984 period, major flow sources include diversions from the Mississippi River (66%), diversions from Centerville Lake/ Rice Creek (18%), local watershed runoff (10%), and direct precipitation on lake surfaces (6%). 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, in turn, reflect consumer demand. The Utility throttles back on diversions from the Mississippi River and Rice Creek during periods of high runoff from the local watershed. Lake level fluctuations are relatively minor. Water treatment includes softening, filtration, and disinfection.

Severe taste-and-odor episodes were experienced at increasing frequencies during the late 1970's and early 1980's. The problem was perceived as related to algal blooms in the supply lakes (Figure 3). Attempts to control these episodes via water treatment (principally, addition of powdered carbon and potassium permanganate) and copper sulfate applications to the supply lakes (weekly during growing season) were largely unsuccessful. Periods of fishy (generally in late Spring or early Summer) and musty (generally in late Summer or early Fall) prompted consumer complaints. An intensive study was initiated in 1984 to identify problem sources and possible solutions.

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 1984-1988 period. Algal counts, 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 number are difficult to establish because of the highly variable nature of lake algal populations, importance of algal type, importance of other organisms (e.g., actinomycetes) which may increase in number following algal blooms and produce taste-and-odor compounds (9,10), and limitations of the threshold odor number measurement. 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 these sources of variability, analysis of 1975-1984 data (5) revealed that the three most severe taste-and-odor episodes on record (intake threshold odor number > 10, accompanied by odor detection in the distribution system and consumer complaints) occurred in June of 1979, 1981, and 1984, and were accompanied by bluegreen algal counts exceeding 5,000 asu/ml. Other, less severe episodes experienced during midsummer and turnover periods typically were accompanied or preceded by bluegreen pulses. Important bluegreen types included Anabaena and, especially, Aphanizomenon.

Because of the extreme potency of the compounds responsible for taste-and-odor and storage of water 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 the importance of high-frequency monitoring to detect algal blooms in supply lakes, if such information is to be used on a "real-time" basis to guide treatment operations. Even with high-frequency monitoring, the feasibility of controlling the problem through chemical dosing or other adjustments in the treatment process is limited, without major capital investments (e.g., granular activated carbon filtration).

Monitoring data from 1984 indicated that algal growth in the supply lakes was limited by phosphorus, nitrogen, and/or silica, depending upon season and lake (5). Epilimnetic total phosphorus and chlorophyll-a concentrations in Vadnais Lake during the summer of 1984 averaged 47 ppb and 19 ppb, respectively, and were indicative of highly eutrophic conditions. Entrainment of phosphorus-rich waters from eroding lake thermoclines in early Fall increased mixed-layer phosphorus concentrations in Pleasant, Sucker, and Vadnais Lakes to the 100-200 ppb range.

Modeling studies (4) indicated that a 50% reduction in summer epilmnetic phosphorus would be required to reduce the frequency of nuisance algal blooms (chlorophyll-a > 30 ppb) from 14% to less than 1%. To predict algal bloom frequency, a model relating mean chlorophyll-a to mean nutrient concentrations was linked with one relating chlorophyll-a interval frequencies to mean chlorophyll-a, based upon the lognormal frequency distribution (11,4). Phosphorus balance calculations (Figure 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 (~2500 kg), and direct precipitation (~34 kg) as factors contributing to the problem.

Continued monitoring through 1984-1986, a period of above-average runoff, provided additional information for diagnosing lake conditions and for designing control measures. The objective of the control program described below is to reduce phosphorus sources sufficiently to restore Vadnais Lake to a mesotrophic status (< 25 ppb), which would be 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 based upon monitoring data from 1984-1988 was hindered by dramatic variations in flow and runoff which were experienced during this period. As shown in Figure 3, regional runoff experienced during 1984-1986 was much greater than that experienced during 1987 (1988, as well).

To some extent, effects of runoff variations on phosphorus loadings to the Vadnais Lake Chain were buffered by the Utility's pumping activity (i.e., during drier periods, more flow was pumped from the Mississippi River). Although local watershed runoff was 7.3 times higher in April-September 1986 vs. 1987, external total phosphorus loading to Vadnais Lake was only 1.8 times higher. Phosphorus releases from lake bottom sediments also tended to reduce the effects of hydrologic variability on lake algal productivity. Longterm time series (Figure 3) indicate no systematic relationship between runoff rate and algal counts. It is unlikely that the lower bluegreen counts observed in Vadnais Lake during 1987-1988 can be attributed to the drought, since counts were much higher during 1980-1981, also a period of below-average runoff (Figure 3).

Results of the 1984-1988 monitoring program are summarized in the following figures:

Figure 5 - Vadnais Lake Epilimnetic Time Series
Figure 6 - Vadnais Lake Time Series by Depth Interval
Figure 7 - Vadnais Lake Seasonal Phosphorus Balances
Figure 8 - Vadnais Intake Algal Counts
Figure 9 - Algal Nuisance Frequencies by Lake and Year

These figures provide a partial basis for evaluating the effectiveness of control measures discussed below. A primary objective of the ongoing monitoring program is to observe lake conditions under a wider 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, nutrient cycling within the lakes, algal blooms, and taste-and-odor episodes (Figure 10). Because of the complexity of the lake chain and lack of single predominant nutrient source, it was apparent initially that several control techniques would be necessary to achieve program objectives. Four major control techniques (Source Selection, Source Treatment, Watershed Management, and Hypolimnetic Aeration) are discussed below.

Source Selection

Source selection refers to the preferential pumping of supply sources based upon lake water quality impact considerations. The

Mississippi River was the predominant supply source during 1978-1984 (66% of lake inflows). The Centerville Lake / Rice Creek source was used primarily during Winter and Spring (19% of lake inflows). Other sources (Otter Lake, Centerville Wells) were also available, but in limited volume (<1% of lake inflows).

Suspension of pumping from Rice Creek was recommended after analysis of 1984 monitoring data, based upon consideration of the nutrient pathways shown in Figure 11 and the source water quality comparisons shown in Figure 12. Since total and ortho phosphorus concentrations were similar, source selection strategy would not have a major direct impact on 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 that lower silica and iron levels in the supply source would tend to promote the undesirable phosphorus pathway leading to bluegreen algal productivity, as opposed to less damaging pathways leading to lake bottom sediments or diatom productivity.

Higher source silica levels would be preferred for the purpose of avoiding depletion of silica from the Vadnais Lake Chain. In May 1984, following a Winter of intensive pumping from Centerville Lake, silica was depleted from Vadnais (Figure 5), as well as from other lakes in the Chain. Silica limitation of spring diatom growth left higher phosphorus concentrations to support summer bluegreen populations. Theoretically, use of the silica-rich source would tend to increase spring diatom growth, but decrease summer bluegreens, which are of primary concern from a taste-and-odor perspective.

Higher source iron levels would be desirable for increasing the phosphorus retention capacity of lake sediments. Hypolimnetic iron/phosphorus ratios in Pleasant and Vadnais Lakes were less than .5 during August of 1984. Ratios exceeding 3 are desirable for promoting iron phosphate precipitation during lake turnover periods (12). 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 (13) and the observed depletion of sulfate from the hypolimnia of Pleasant and Vadnais lakes during summer 1984, production of insoluble iron sulfide compounds was a major factor contributing to iron deficiency. Iron is also an important factor regulating phosphorus releases from shallow lake sediments (14). Use of an iron-poor source (Centerville Lake) would promote iron deficiency and phosphorus recycling from lake sediments. Use of the Mississippi River (particularly in combination with iron injection and aeration) would promote iron enrichment and phosphorus retention.

Based upon the above hypotheses, pumping from Centerville Lake was suspended in Fall 1984. The Mississippi River was pumped exclusively until July of 1988, when an extreme draught forced the Utility to pump from Centerville Lake for a period of approximately three weeks. Observed lake responses include higher silica levels in all lakes during 1985-1988 and the avoidance of silica-limited conditions (Figure 5). In Vadnais Lake, peak diatom counts in Spring 1985 and 1986 were approximately twice those observed in 1984 (Figure 8), but did not trigger a taste-and-odor episode. Peak bluegreen populations in Vadnais Lake decreased each year following 1984. Accumulation of phosphorus in the Vadnais Lake hypolimnion also decreased between 1984 and 1986. Although it is impossible to "prove" that these changes resulted from the recommended source pumping strategy, the observations were consistent with the above hypotheses and the observed changes were in a favorable direction.

Source Treatment

Source treatment refers to the addition (or removal) of chemicals from the pumped diversions for the purpose of reducing lake impacts. Several alternatives were considered, primarily with respect to the Mississippi River source. Obviously, it would be desirable (though costly) to remove phosphorus via physical/chemical treatment, as demonstrated by Bernhardt (15) in the case of Wahnbach Reservoir, Germany. While such a measure was not ruled out, a less extreme and less costly alternative, phosphate deactivation by iron chloride injection, was implemented on a trial basis in Spring of 1987. This technique has been successfully applied to reduce algal growth in other water supply systems with river pumping and lake storage components in England (16) and the Netherlands (17).

Phosphate ions adsorb to insoluble ferric hydroxides which are formed when iron chloride solution is injected into water pumped from the River. Although reversible, this process renders ortho phosphorus less available to stimulate algal growth in the downstream lakes. Factors such as pH, mixing, temperature, and oxidation-reduction potential can influence the process (18). Aluminum sulfate could also be used for this purpose and would be less susceptible to phosphate release under low-redox conditions. Use of alum in place of iron chloride in this case would require much higher doses (> 10 ppm Al vs. ~.5-1 ppm Fe) because of high alkalinity (~150 ppm). Risk of toxicity problems would also be higher for alum as compared with iron. Based upon average concentrations in the Mississippi River (Total P = 122 ppb, Ortho P = 33 ppb, Figure 12), iron treatment to reduce ortho phosphorus concentrations to less than 10 ppb would remove 70% of the ortho phosphorus load from the River. Subsequent sedimentation of the insoluble iron-phosphate complexes would remove 19% of the total phosphorus load. The success of such a process would depend upon the reversibility of the iron/phosphate reactions in the downstream lake environments, which could be evaluated using a whole-lake experimental approach.

Laboratory and field-scale tests were performed to evaluate dose-removal relationships in samples taken from the Mississippi River and from other locations in the Vadnais Lake chain (7). Results showed that removal ratios (ortho P removed / iron added) ranged from .01 to .28 and increased with solution ortho P and decreased with iron dose. A full-scale field test was conducted in July of 1986 (Figure 13). Iron chloride (liquid, ~13% Fe by weight) was injected into the water pumped from the River. The flow passed through 15-km underground conduits, through Charley Lake (a shallow, 12-ha lake with a hydraulic detention time of approximately 1 day), and subsequently into Pleasant Lake. Five, week-long dose levels (0, .5, 1, 2, and 0 ppm Fe) were tested. Phosphorus, iron, and other water quality measurements were collected twice daily at three locations: River (before injection), conduit outlet, and Charley Lake outlet.

Ortho phosphorus time series at each station are shown in Figure 13. Results indicated significant reductions in ortho phosphorus levels in the conduit and lake outflow following injection of iron chloride. At the lowest non-zero dose tested (.5 ppm Fe), the average ortho phosphorus level at the lake outflow station was reduced from 45 to 13 ppb. Since higher doses did not result in significant further reductions at the lake outflow station, the .5 ppm dose was recommended for full scale implementation. Most of the injected iron was removed via sedimentation in Charley Lake.

Iron chloride has been injected at the SPWU Mississippi River pumping station since April 1987. Evaluation of impacts on the Vadnais Lake chain has been difficult because of the significant reductions in flow and phosphorus in the Mississippi River experienced during the 1987-1988 drought. Average ortho phosphorus levels in the River dropped from 38-44 ppb in 1984-1986 (wet years) to 18 ppb in 1987 and 1988 (dry years). This reflected less runoff, lower flow velocities, and increased algal growth in the Mississippi River during dry periods. Although Pleasant Lake phosphorus concentrations, bluegreen algal densities, and algal nuisance frequencies (Figure 9) were lower in 1987-1988 as compared with 1984-1986, monitoring over a longer time frame will be required to evaluate the impacts of iron injection on Pleasant Lake and others lakes in the Vadnais Chain.

Watershed Management

Monitoring stations in the local watershed revealed 5- to 10-fold higher rates of runoff and phosphorus export from urban vs. undeveloped watersheds in the lake chain (4,5). Significant urban growth was (and is) occurring in the local watershed, particularly along Lambert Creek, which discharges directly into Vadnais Lake. Mass-balance modeling (4) indicated that with projected full development of the watershed, Vadnais Lake total phosphorus concentration would increase from 47 to 59 ppb and the frequency of intake chlorophyll-a concentrations exceeding 30 ppb would increase from 14 to 26%. This situation clearly indicated a need to reduce the impacts of existing and future urban development, given the Utility's need to control taste-and-odor and other undesirable impacts of eutrophication. The watershed management program described below is not expected to provide immediate benefits in terms of lake improvement, but is viewed as an investment which is critical to longterm protection of Vadnais Lake and its use as a water supply.

To address the impacts of future development, the Utility worked with local communities to develop a Watershed Management Plan (19). The plan included inventories of watershed resources, existing and future land uses, and specification of management practices to reduce urban runoff and its effects on the lakes. Derived primarily from EPA's Nationwide Urban Runoff Program, design criteria for detention ponds were incorporated into the Plan (20). 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 50%-60%.

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

Hypolimnetic Aeration

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

Hypolimnetic aeration can be an effective technique for reducing the accumulation of phosphorus in lake bottom waters (21,22,23,24). Two hypolimnetic aeration units ("LIMNOs" furnished by Aqua Technique, Inc.) were installed in Vadnais Lake in November 1986. The objective of aeration was to maintain an aerobic sediment/water interface throughout the year and thereby reduce that portion of the phosphorus recycling which was attributed to low redox conditions. This would, in turn, 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 1984-1988 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 the aerator effectiveness 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 (Figure 14) showed hypolimnetic (10-16 m) oxygen concentrations decreasing from 3-4 ppm in the immediate vicinities of the aerators (North and South stations) to 2-3.5 ppm at other stations (North End, Central, South End). Consistent with observations by Taggart (25) and McQueen and Lean (26), the aerators appeared to have limited influence on oxygen concentrations in the thermocline (7-9 meters), where distinct oxygen minima were observed at all stations.

Hypolimnetic responses to aeration included reductions in ammonia and kjeldahl nitrogen levels and increases in nitrate and sulfate levels. Seasonal variations in hypolimnetic dissolved oxygen and ortho phosphorus concentrations are plotted in Figure 15. One effect of aeration was to eliminate thermal stratification (Figure 6) and loss of hypolimnetic dissolved oxygen during Winter. Associated accumulation of ortho phosphorus in the hypolimnion under ice cover was also eliminated, based upon a comparison of ortho phosphorus levels in March 1985 and 1986 (.1-.5 ppm) with levels in March 1987 and 1988 (< .04 ppm). These reductions were important because they influenced the supply of ortho phosphorus at spring turnover. As indicated in Figure 8, maximum spring diatom counts and chlorophyll-a levels were also lower in 1987 and 1988, as compared with 1986 and 1987 (silica limited peak diatom levels in Spring 1984).

Beneficial impacts of hypolimnetic aeration on phosphorus cycling are dependent upon iron availability (26,27). As discussed above (see Source Selection), both the hypolimnion and bottom sediments of Vadnais Lake were found to be deficient in iron from a phosphorus control perspective. Seasonal mass balances indicated that aeration alone had little influence on net phosphorus sedimentation in April-September 1987 (Figure 7). Although total phosphorus concentrations in the epilimnion (Figure 5) and hypolimnion (Figure 6) were lower in 1987 than they had been in previous years, these decreases may have been related more to the lower runoff and external loadings during 1987 than to the impacts of aeration.

A full-scale experiment conducted during the summer of 1988 indicated that injecting iron chloride into the aerators could significantly decrease hypolimnetic phosphorus accumulations and increase phosphorus retention by lake sediments. Iron chloride was injected continuously at the base of the aerators (just above air diffuser rings) from June 30 thru October 1, 1988. Measured rates of phosphorus accumulation in the hypolimnion ranged from 7 kg/day (May-August 1987) to

17 kg/day (May-August 1985). For this range of accumulation, the iron injection rate selected for the full-scale experiment (100 kg Fe/day) corresponded to a removal ratio of .07 to .17 g Ortho P/ g Fe, which was consistent with results of laboratory dosing experiments on hypolimnetic waters (.10-.28 g/g) and with the .10 g/g removal ratio reported by Lean et al. (27) for a similar full-scale experiment.

As shown in Figure 15, accumulation of ortho phosphorus in the hypolimnion was reversed when iron injection began at the end of June 1988. Consistent with oxygen measurements, good horizontal distribution of treatment effectiveness 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 aerator. During the next two weeks, the dose was injected into the north unit. During the last six weeks, the dose was alternated on a daily basis between the south and north units. Hypolimnetic phosphorus measurements in each lake region showed rapid response to iron injection (Figure 16). Considerable horizontal transport within the hypolimnion was indicated by the fact that ortho P concentrations in the northern lake began to decrease during July, when iron was being injected only at the south unit. The steady increase of ortho phosphorus at 8 meters during dosing periods suggests that penetration of the treatment effectiveness into the thermocline was limited. The apparent result of iron dosing in combination with hypolimnetic aeration was to substantially reduce the ortho and total phosphorus concentrations at fall turnover in 1988 (35 ppb vs. 100-200 ppb for previous years, Figure 5). Net phosphorus retention by lake sediments during April through September ranged from -854 to 281 kg in 1984-1987, as compared with 1763 kg in 1988 (Figure 7).

Despite substantial reductions in hypolimnetic phosphorus attributed to the iron treatment, algal blooms developed in late August and early September 1988, when chlorophyll-a exceeded 30 ppb (Figure 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 and resulting entrainment of ortho phosphorus into the mixed layer. Most of the metalimnetic phosphorus accumulation occurred prior to initiation of iron injection at the end of June. Starting iron injection earlier in the season when the thermocline is higher (early May vs. late June) may help to reduce metalimnetic buildup of ortho phosphorus and resultant risk of algal blooms during late Summer.

One remaining uncertainty is the extent to which the effectiveness of the iron treatment will penetrate into the thermocline region. Another uncertainty is the longevity of the treatment. Based upon sedimentation rates estimated via Pb-210 dating (13) the total mass of iron injected during 1988 (~9,200 kg) was the equivalent of 130 to 210% of the existing iron sedimentation rate, or 41% of the total mass of iron stored in the top 2 centimeters of hypolimnetic sediment prior to treatment. Ideally, continued iron injection over a few seasons, in combination with reduced algal productivity and efficient aeration, would replenish the iron content in the bottom sediments and provide longterm benefits. This would reduce the need for continuous injection of iron, provided that aerobic conditions are maintained. Some of the phosphorus which is intercepted by the iron treatment may be unrelated to bottom sediment conditions, however (e.g., phosphorus released from decaying seston, particularly after the spring diatom bloom). Interception of this phosphorus may require longterm iron injection. The feasibility of enriching lake bottom sediments via this technique also depends upon the horizontal pattern of iron deposition around the aerators, which has yet to be evaluated. Gradual oxidation of the sediments under aerobic conditions may have beneficial impacts on phosphorus cycling which would be detectable only over time scales longer than two years. The short-term strategy is to continue with the iron injections during the summer stratified period until more is learned about lake responses and the dose regime can be "optimized".

Other Control Measures

Several other control techniques are being evaluated (Figure 10). To help reduce phosphorus transport from the upper lake chain, hypolimnetic aeration has been recommended for Pleasant Lake (8). A multi-level intake structure for Vadnais Lake to permit use of hypolimnetic or metalimnetic waters during periods of surface algal blooms is being investigated (28). In the local watershed, preliminary designs for regional detention basins on the mainstem of Lambert Creek (Figure 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 the above nutrient-based control strategies is being considered. Continued monitoring of the watershed and lake chain will provide a basis for evaluating and refining the control techniques under a wider range of hydrologic conditions.

RELATED IMPACTS

Subject to uncertainties associated with varying flow conditions, observed lake responses over the 1984-1988 period suggest that progress has been made towards the goal of 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 would also be expected to have beneficial impacts on chlorinated hydrocarbons and treatment costs. Treated-water trihalomethane (THM) concentrations and chemical costs for 1984-1988 are shown in Figure 17. Chemical costs have been computed from daily doses and normalized to 1988 chemical prices and an average flow of $.19 \times 10^6\ m^3$/day (50 mgd). Chemicals have been divided into three categories, based upon probable sensitivity to source eutrophication. The costs of powdered carbon and potassium permanganate (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.

The apparent decreasing trends in THM levels and chemical costs are consistent with improved lake water quality, although other factors may be involved. For example, lower THM levels in 1987 and 1988 may be partially related to a change in the water treatment process (application of chlorine dioxide). Cost savings attributed to reductions in potassium permanganate and powdered carbon doses amounted to approximately $300,000/year between 1984 and 1988. Net economic impacts should be evaluated based upon a longer period of record and considering the costs of eutrophication controls. Amortized capital and operating costs associated with iron chloride injection at the Mississippi River and hypolimnetic aeration / iron chloride injection at Vadnais Lake total approximately $150,000 per year. A strictly economic evaluation of the program is infeasible because the desired water quality benefits (reducing the frequency/severity of taste-and-odor episodes; lower THM levels) cannot be expressed in terms of dollars. Based upon these experiences, however, it is not unreasonable to expect that costs of nutrient-based controls would be offset partially, if not completely, by reduced water treatment costs.

CONCLUSIONS

Observed responses in the lakes and water treatment plant suggest that the nutrient-based control strategy (Figure 10) has been effective in reducing algal growth in the supply lakes, the risk of taste-and-odor episodes, and other undesirable impacts of eutrophication on the water supply. This progress has been facilitated by commitments of the Utility to the intensive monitoring and whole-lake experimental programs described above. Additional studies are required to evaluate lake responses under a wider range of hydrologic conditions, to refine the control measures, and to quantify longterm benefits.

REFERENCES

1. Bernhardt, H., "General Impacts of Eutrophication on Potable Water Preparation", in "Restoration of Lakes and Inland Waters", U.S. Environmental Protection Agency, EPA-440/5-81-010, pp. 359-363, December 1980.

2. Walker, W.W., "Significance of Eutrophication in Water Supply Reservoirs", Journal of the American Water Works Association, pp. 38-42, January 1983.

3. Palstrom, N.S., R.E. Carlson, G.D. Cooke, "Potential Links Between Eutrophication and the Formation of Carcinogens in Drinking Water", Lake and Reservoir Management, Vol. 4, No. 2, pp. 1-15, 1988.

4. Walker, W.W., "Urban Nonpoint Source Impacts on a Surface Water Supply", in "Perspectives on Nonpoint Source Pollution", Proceedings of a National Conference, Kansas City, Mo., U.S. Environmental Protection Agency, EPA 440/5-85-001, pp. 129-137, May 1985.

5. Walker, W.W., "Analysis of 1984 Monitoring Data from the Vadnais Lakes Diagnostic Study", prepared for Board of Water Commissioners, St. Paul, Minnesota, June 1985.

6. Walker, W.W., "Analysis of 1985 Monitoring Data from the Vadnais Lakes Diagnostic Study", prepared for Board of Water Commissioners, St. Paul, Minnesota, August 1986.

7. Walker, W.W., "Analysis of 1986 Monitoring Data from the Vadnais Lakes Diagnostic Study", prepared for Board of Water Commissioners, St. Paul, Minnesota, August 1987.

8. Walker, W.W., "Analysis of 1987 Monitoring Data from the Vadnais Lakes Diagnostic Study", prepared for Board of Water Commissioners, St. Paul, Minnesota, December 1988.

9. Gerber, N.N. and H.A. Lechevalier, "Geosmin and Earthy-Smelling Substances Isolated from Actinomycetes", Applied Microbiology, Vol. 13, No. 6, pp. 935-938, 1965.

10. Bratzel, M.P., M.E. Thompson, R.J. Dowden, eds., "The Waters of Lake Huron and Lake Superior. Vol. II (Part A). Lake Huron, Georgian Bay, and the North Channel", report to the Inter. Joint Commission by the Upper Lakes Reference Group, Windsor, Ontario, 1977.

11. Walker, W.W., "Statistical Bases for Mean Chlorophyll-a Criteria", Proceedings of International Symposium on Lake and Reservoir Management, Fourth Annual Meeting, North American Lake Management Society, McAfee, New Jersey, pp. 57-62, October 1984.

12. Stauffer, R.E, "Sampling Strategies for Estimating the Magnitude and Importance of Internal Phosphorus Supplies in Lakes", U.S. Environmental Protection Agency, Corvallis Laboratory, EPA-600/3-81-015, April 1981.

13. Engstrom, D.R., "Lake Sediment Survey", prepared for St. Paul Water Utility, Limnological Research Center, Univ. of Minnesota, 1986.

14. Ripl, W., "Internal Phosphorus Recycling Mechanisms in Shallow Lakes", in "Lake and Reservoir Management", Volume II, North American Lake Management Society, Proceedings of Fifth Annual Conference, Lake Geneva, Wisconsin, pp. 138-142, 1986.

15. Bernhardt, H., "Reservoir Protection by In-River Nutrient Reduction", in "Restoration of Lakes and Inland Waters", U.S. Environmental Protection Agency, EPA-440/5-81-010, pp. 272-277, December 1980.

16. Hayes, C.R., R.G. Clark, R.F. Stent, C.J. Redshaw, "The Control of Algae by Chemical Treatment in a Eutrophic Water Supply Reservoir", Journal of the Institution of Water Engineers and Scientists, Vol. 38, No. 2, pp. 149-162, April 1984.

17. Bannink, B.A. and J.C. VanDer Vlugt, "Hydrobiological and Chemical Response to the Addition of Iron and Aluminum Salts, Studied in Three LUND-Type Butlyrubber Reservoirs", Verh. Internat. Verein. Limnol., Vol. 20, pp. 1816-1821, November 1978.

18. Lijklema, L. "Interaction of Orthophosphate with Iron (III) and Aluminum Hydroxides:, Environmental Science and Technology, Vol. 14, No. 5, pp. 537-541, May 1980.

19. Vadnais Lake Area Water Management Organization, Watershed Management Plan, Minnesota, 1986.

20. Walker, W. W., "Phosphorus Removal by Urban Runoff Detention Basins", in Lake and Reservoir Management, Volume III, North American Lake Management Society, pp. 314-326, 1987.

21. Bernhardt, H. "Ten Years' Experience of Reservoir Aeration", Progress in Water Technology, Vol. 7, No. 3/4, pp. 483-495, 1975.

22. Smith, S.A., D.R. Knauer, T.L. Wirth, "Aeration as a Lake Management Technique", Wisconsin Dept. of Natural Res. Tech. Bull. No. 87, 39 pp., 1975.

23. Fast, A.W. and M.W. Lorenzen, "Synoptic Survey of Hypolimnetic Aeration", Journal of the Environmental Engineering Division, American Society of Civil Engineers, Vol. 102, pp. 1161-1173, 1976.

24. Pastorok, R.A., T.C. Ginn, M.W. Lorenzen, "Evaluation of Aeration/Circulation as a Lake Restoration Technique", U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon, EPA-600/3-81-014, February 1981.

25. Taggart, C.T., "Hypolimnetic Aeration and Zooplankton Distribution: A Possible Limitation to the Restoration of Cold-Water Fish Production", Canadian Journal of Fisheries and Aquatic Sciences, Vol. 41, no. 1, pp. 191-198, 1984.

26. McQueen, D.J. and D.R.S. Lean, "Hypolimnetic Aeration: An Overview", Water Poll. Res. J. Canada., Vol. 21, No. 2, pp 205-217, 1986.

27. Lean, D.R.S., McQueen, D.J., and V.A. Story, "Phosphate Transport During Hypolimnetic Aeration", Arch. Hydrobiol., Vol. 108, No. 2, pp. 269-282, December 1986.

28. Owens, E.M., "Hydrothermal and Water Quality Modeling and Analysis of Vadnais Lake", prepared for Board of Water Commissioners, St. Paul, Minnesota, December 1988.

Figure 1
Cause-Effect Pathways

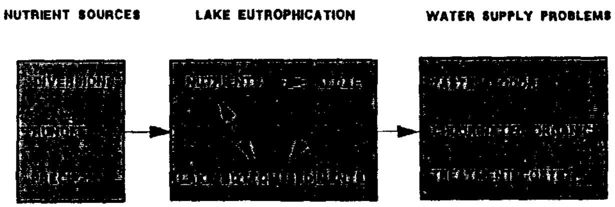


Figure 2
St. Paul Supply System

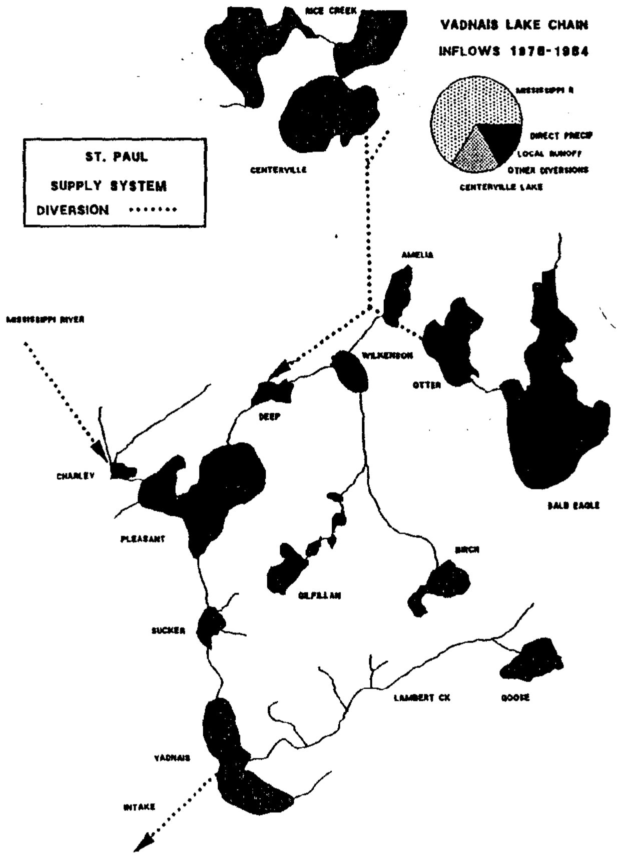


Figure 3
Weekly-Mean Bluegreen Algal Counts and Regional Runoff

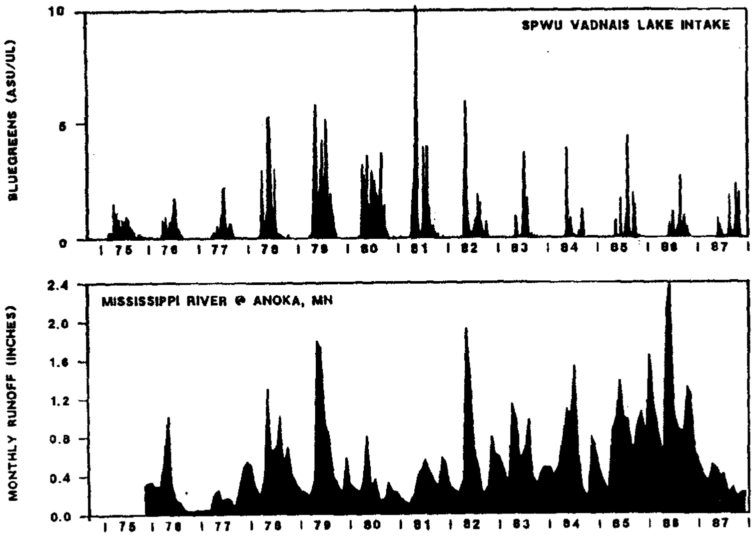


Figure 4
Vadnais Lake Phosphorus Balance for April-September 1984

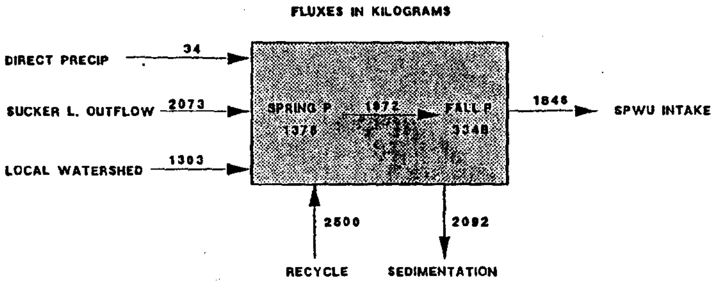
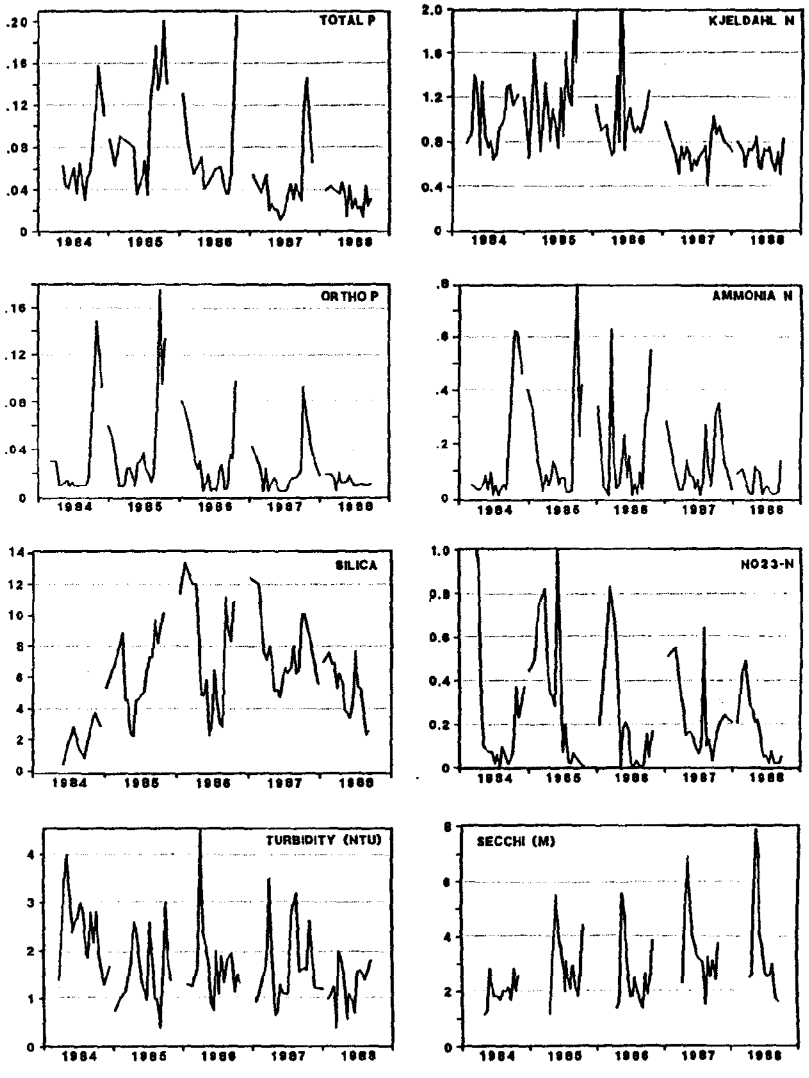


Figure 5
Vadnais Lake Epilimnetic Time Series



CONCENTRATIONS IN PPM

Figure 6
Vadnais Lake Temperature, Oxygen, and Total Phosphorus Time Series by Depth Interval

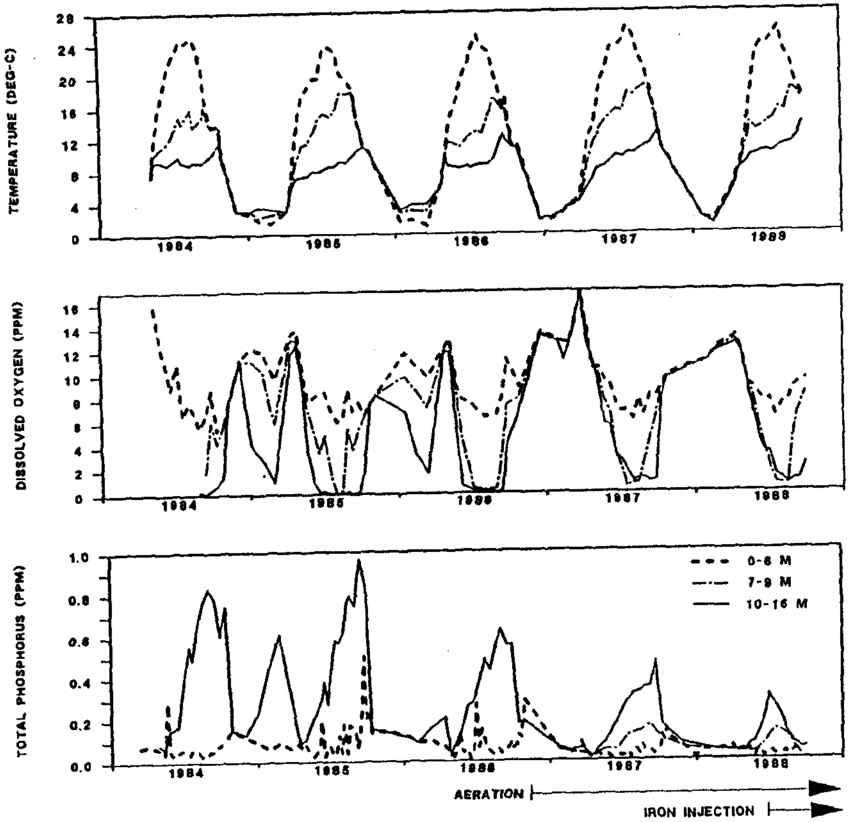


Figure 7
Vadnais Lake Seasonal Phosphorus Balances

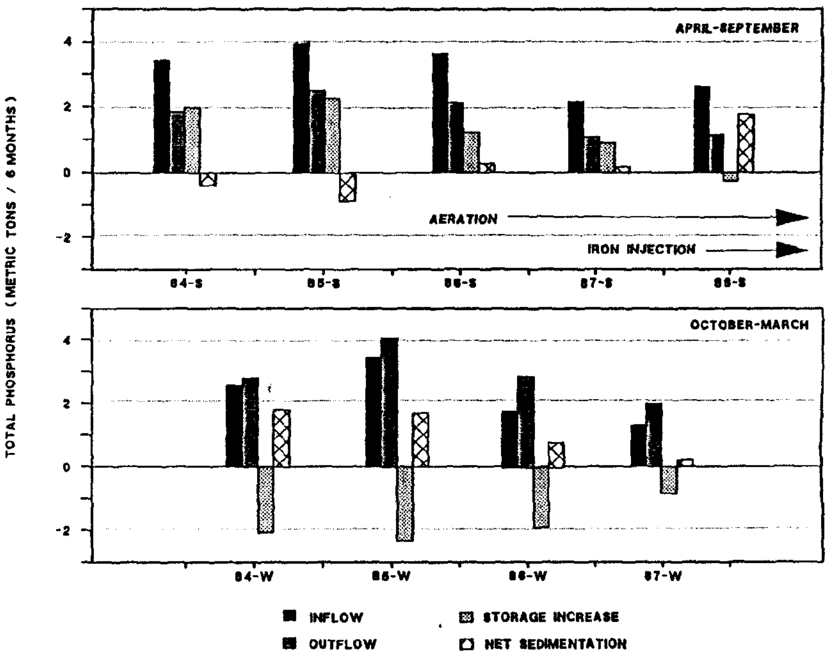


Figure 8
Vadnais Intake Algal Counts

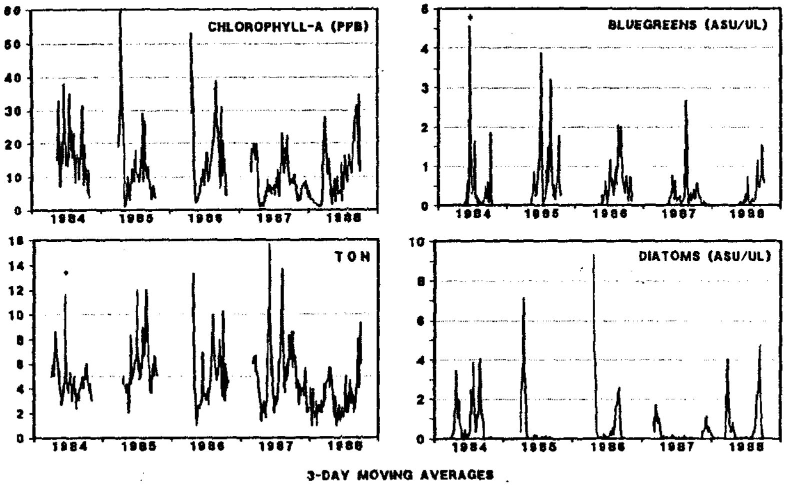


Figure 9
Algal Nuisance Frequencies by Lake and Year

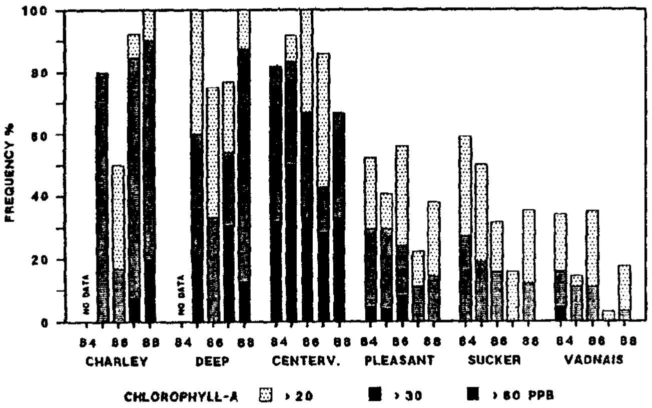


Figure 10
Taste-and-Odor Control Strategy

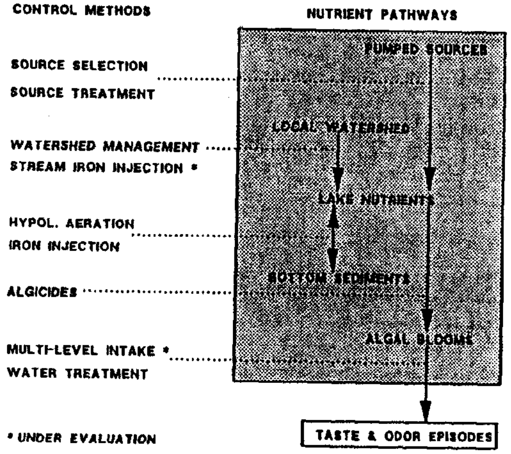


Figure 11
Nutrient Pathways

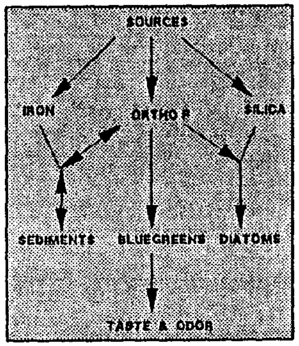


Figure 12
SPWU Source Comparisons

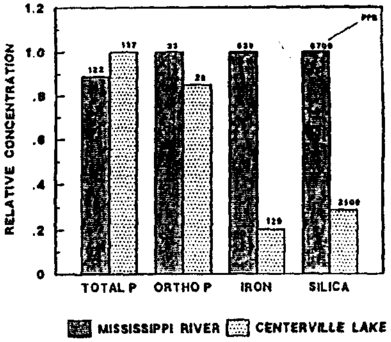


Figure 13

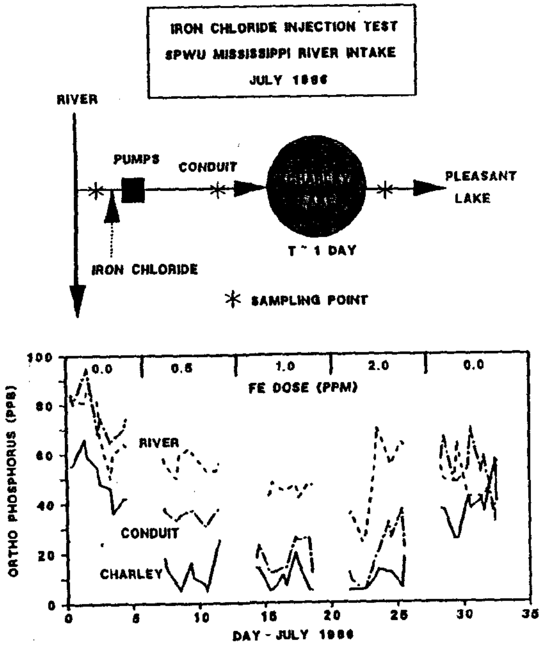


Figure 14
Oxygen Profiles - July 5, 1988

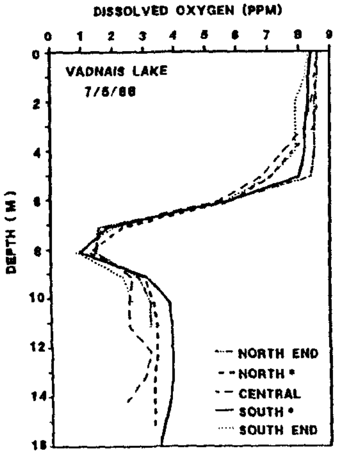


Figure 15
Seasonal Variations in Dissolved Oxygen and Ortho Phosphorus
Vadnais Lake Hypolimnion 1984-1988

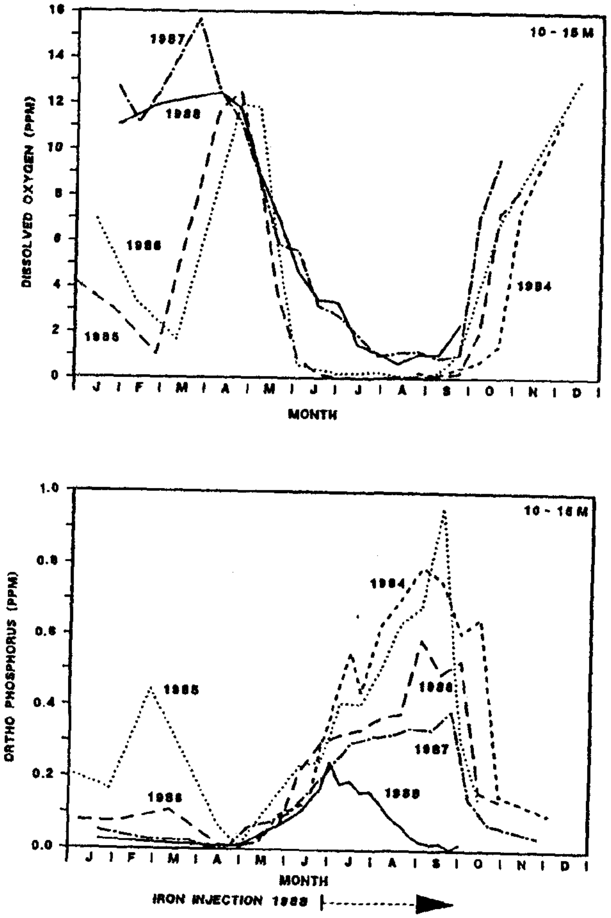


Figure 16
Ortho Phosphorus Responses to Iron Chloride Injection in Northern and Southern Lake Regions

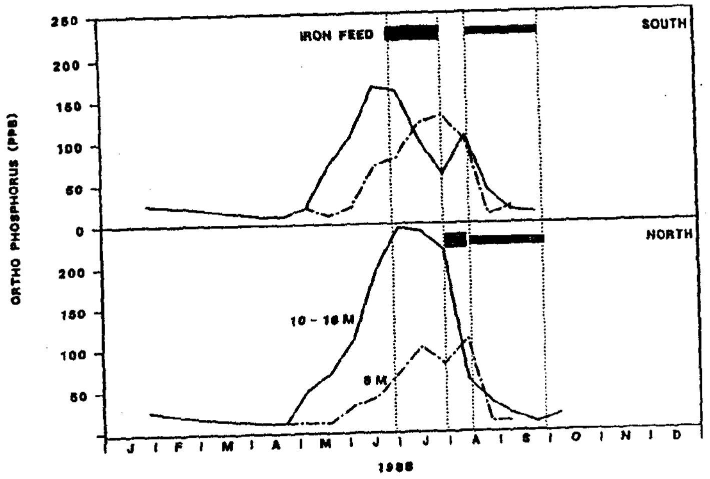
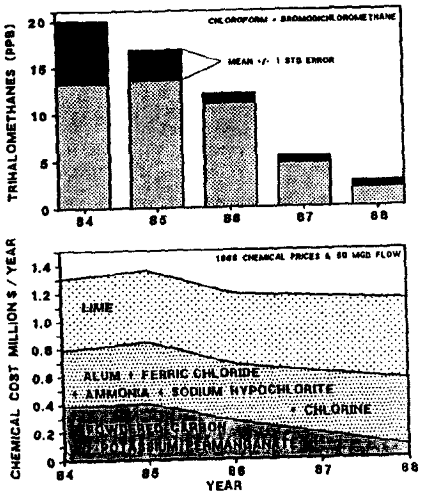


Figure 17
Treated-Water Trihalomethanes and Total Chemical Costs 1984-1988



ARTIFICIAL DESTRATIFICATION AND ITS EFFECT ON WATER QUALITY IN AN IMPOUNDMENT

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INTRODUCTION

Lakes have the potential to stratify into three distinct layers during the summer as a result of sunlight heating the top layer (Ruttner, 1963). In all but oligotrophic lakes, the bottom layer generally becomes anoxic as a result of bacterial decomposition of organic matter that settles to the bottom (Charlton, 1980). During these periods of anoxia, the chemistry of the bottom water changes (Faust and McWhorter, 1976). If the lake also serves as a public water supply, then these chemical changes can affect the taste, odor, and color of the water such that additional treatment may be required in order to insure a potable and aesthetically pleasing water at the tap (Jamerson and Tantum, 1986).

The T. Howard Duckett Reservoir is a deep water impoundment located about half way between Washington, D.C. and Baltimore, MD. on the headwaters of the Patuxent River. The reservoir, which is owned and operated by the Washington Suburban Sanitary Commission (WSSC), supplies potable water to the Maryland counties adjacent to Washington, D.C.. The reservoir has had a history of thermally stratifying in the summer. This, in turn, has caused all sorts of water quality problems in the reservoir and at the water treatment plant. One way that WSSC has chosen to protect its raw water supply is to artificially destratify the reservoir using bubble-tube aerators.

WSSC installed the bubble-tube aerators in July 1985 and have operated them more or less continuously since then from early spring to late fall. A "before/after" study was conducted to