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PHYSICAL AND CHEMICAL WATER QUALITY CHARACTERISTICS OF THE FOX CHAIN OF LAKES

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ABSTRACT

The Fox Chain of Lakes experiences luxuriant and prolonged algal blooms, periodic fish kills, offensive odors, and other symptoms of the advanced stage of eutrophication. All the deep lakes in the chain stratify thermally and the hypolimnetic zones are totally devoid of oxygen. In the shallow lakes, even though the temperatures are uniform, or nearly so, for the entire depth, there is a significant drop in dissolved oxygen near the bottom of the lake. The oxygen demands exerted by the bottom sediments are much higher than the oxygen replenished from the atmosphere during the summer months.

The lake waters are high in alkalinity and hardness, typical of midwestern surface waters. The pH values of lake surface water samples were never less than 8.0 during this investigation. This is indicative of active photosynthesis in which carbon dioxide is utilized from the bicarbonate alkalinity. Deep water samples had pH values less than 8.0 generally when the bottom sediments were undergoing anaerobic decomposition.

The mean nitrate concentrations in all the lakes and at all depths examined were similar. The dissolved orthophosphorus concentrations in the deep water zones were observed to be several orders of magnitude higher than the values determined for surface and mid-depth water samples in these lakes. The phosphorus and nitrogen concentration levels in the lakes were much higher than the critical levels of nutrient concentrations suggested in the literature.

INTRODUCTION

The Fox Chain of Lakes consists of nine major internally connected lakes located in Lake and McHenry Counties in northern Illinois. The

inflow into the lake system is the Fox River. Other tributaries of importance are the Sequoit, Nippersink, and Squaw Creeks, and Lily Lake Drain. The drainage area of the Fox River at Johnsburg, immediately downstream of the Fox Chain of Lakes, is 3,066.56 square kilometers. Approximately 75 percent of the drainage area lies in Wisconsin.

The surface water levels of the system are maintained by a dam at McHenry. At normal pool elevation, the water surface area of the lake system is about 2772 hectares. The shoreline extends 77 kilometers and there is an additional 48 kilometers of dredged channel shoreline to accommodate demands for lake frontage property.

The lakes and their associated shorelands constitute a natural valuable resource that is showing the effects of use and abuse by more and more people. Nuisance algal blooms have been a source of recorded complaints on the Chain for at least the past 35 years. Such protests expressed apprehension regarding the curtailment of bathing, boating, water skiing, fishing, lowering of property values, cancellation of resort trade, and impairment of the picturesque beauty of the Chain. Luxuriant and prolonged algal blooms, periodic fish kills, and offensive odors have been reported during many investigations (Illinois Department of Conservation, 1964; Lake County Health Department, 1962; and U. S. Public Health Service, 1963).

Existing physical and chemical water quality characteristics in the Fox Chain of Lakes are presented in this report. Biological characteristics with particular emphasis on phytoplankton are reported elsewhere (Lin et al.).

MATERIALS AND METHODS

In order to assess the physical, chemical, and biological characteristics of the lake system, field trips were undertaken to make *in situ* observations of temperature, dissolved oxygen, and secchi disc readings and to obtain water samples for chemical and biological evaluations. Biweekly trips were made during the period May 19, 1975, to July 14, 1975, and thereafter weekly trips were made until October 20, 1975.

Fourteen lake stations were established for water sampling and *in situ* observations (Figure 1). These sampling sites were selected at the deepest part of each of the lakes. In waters with depths greater than 9.1 meters, as in the case of Lakes Catherine, Channel, Marie (west basin), and Pistakee Bay, water samples were obtained at three different depths -- at the surface, mid-depth, and 0.3 meter from the bottom, here designated as the deep sample. In the lakes with maximum depths in the range of 4.6 to 9.1 meters, water samples were obtained from surface and deep locations. In all other cases, only water samples from the surface were collected.

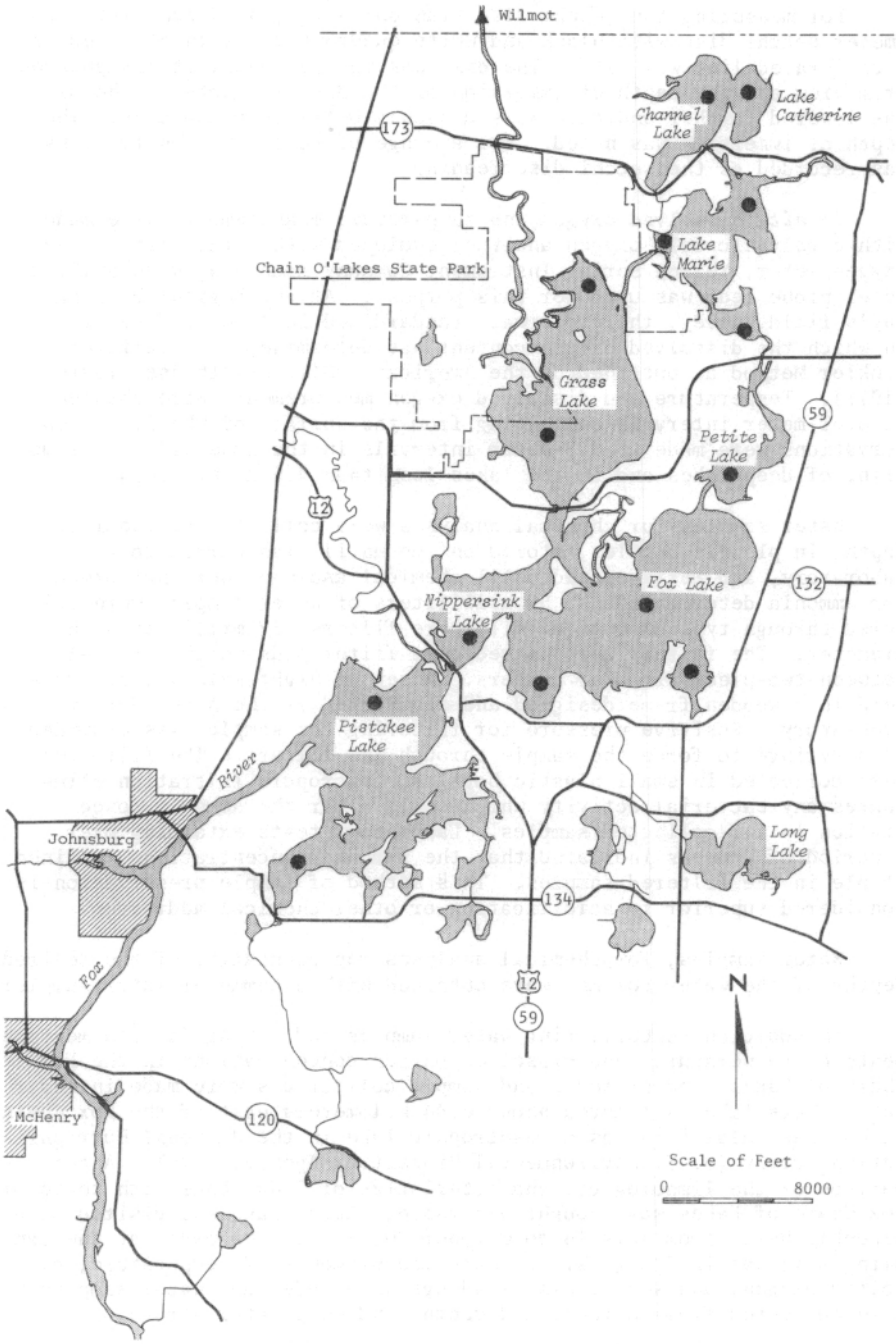

FIGURE 1.--Fox Chain of Lakes showing sampling locations.

For measuring the secchi disc transparencies, a 20-centimeter diameter secchi disc with black and white quadrant markings attached to a calibrated line was used. The disc was lowered until it disappeared from view and the depth of immersion of the disc was noted. The disc was lowered farther and then raised slowly until it reappeared. The depth of immersion was noted. The average of these two observations was recorded as the secchi disc reading.

In situ dissolved oxygen and temperature measurements were made with a galvanic cell oxygen analyzer equipped with a thermister. An oxygen meter, Yellow Spring Instrument Company model 54, with a 15.24-meter probe lead was used for this purpose. At the beginning of each day's field survey, the probe was standardized in lake surface water in which the dissolved oxygen content was determined by a modified Winkler Method as outlined by the American Public Health Association (1971). Temperature and dissolved oxygen measurements were obtained at 0.61-meter intervals commencing from the surface of the lake. Observations were made at 0.3-meter intervals in the zone of the thermocline of deep lakes and in the lakes less than 4.6 meters deep.

Water samples for chemical analyses were collected at required depths in plastic bottles, stored on ice until transported to the laboratory, and refrigerated until chemical analyses were performed. For ammonia determinations, 50 milliliters of water samples were filtered through type HA 0.45 μm millipore filters, 37 millimeters in diameter. The filters were placed over filter pads which were held between two-piece circular holders. A set of eight such holders were held in a wooden frame designed and fabricated at the Water Survey laboratory. Positive pressure for filtering the samples was provided by a syringe to force the sample through the filters. The filtrates were collected in small plastic bottles. Micropore filtration eliminates any bacterial activity which could alter the ammonia concentration in the collected samples. Laboratory tests extending over a period of 4 weeks indicated that the ammonia concentrations remained stable in the filtered samples. This method of sample preservation is considered superior to acidification or other chemical additives.

Water samples, for chemical analyses representative of the desired depths of the water column, were obtained with a Kemmerer water sampler.

In addition to collecting water samples and making *in situ* measurements of temperatures and dissolved oxygen concentrations in the Fox Chain of Lakes, measurements and sample collections were made in Cedar Lake. This lake is located about 6.44 kilometers east of the Fox Chain. It has been classified as a mesotrophic lake in the National Eutrophication Survey (U. S. Environmental Protection Agency, 1975). A comparison of the limnological characteristics of Cedar Lake with those of Fox Chain of Lakes was thought desirable. Cedar Lake was visited on a biweekly basis from July 14 to October 20, 1975. The depth at the sampling site was 12.8 meters. *In situ* measurements of temperature, dissolved oxygen, and secchi disc readings were made, and water samples were collected from surface, mid-depth, and deep water strata.

TABLE 1. Analytical Procedures

Turbidity	Nephelometric method, using Turner Fluorometer, Model 110; Formazin was used as a standard
pH	Glass electrode method using Leeds and Northrup 7401 and later Beckman 4500
Alkalinity	Potentiometric method
Hardness	EDTA titrimetric method
Nitrate-N	Chromatropic method (West, 1966)
Kjeldahl-N	Kjeldahl digestion and ammonium determined by phenate method
Ammonium-N	Phenate method
Total silica	Molybdosilicate method
Total iron	Phenonthroline method
Chloride	Argentometric method
Sulfate	Turbidimetric method
Total dissolved solids	Residue on filtration and evaporation at 103 to 105°C
Total phosphorus	Sample was digested with sulfuric-nitric acids mixture and determined by ascorbic acid method
Dissolved orthophosphorus	Ascorbic acid method after filtration through 0.45 μm filter paper

Note: Unless otherwise stated all the methods used were according to *Standard Methods* (American Public Health Association, 1971)

The following physical and chemical determinations were made on water samples in the laboratory: turbidity, pH, alkalinity, hardness, nitrate-nitrogen, Kjeldahl nitrogen, ammonia-nitrogen, total silica, total iron, chloride, sulfate, total solids, dissolved solids, suspended solids, total phosphorus, and dissolved orthophosphorus. The methods and procedures involved in these determinations are shown in Table 1.

PHYSICAL CHARACTERISTICS

Temperature and Dissolved Oxygen

Lakes in the temperate zone generally undergo seasonal variations in temperature through the water column (Kothandaraman and Evans, 1970). These variations, with their accompanying phenomena, are perhaps the most influential controlling factors within the lakes.

Figure 2 shows the isothermal plots for Lake Catherine which is typical of the deep lakes in the Chain. At the time of the first observation for temperature profiles, on May 19, 1975, the deep lakes in the Fox Chain had already begun to stratify. The lake surface water

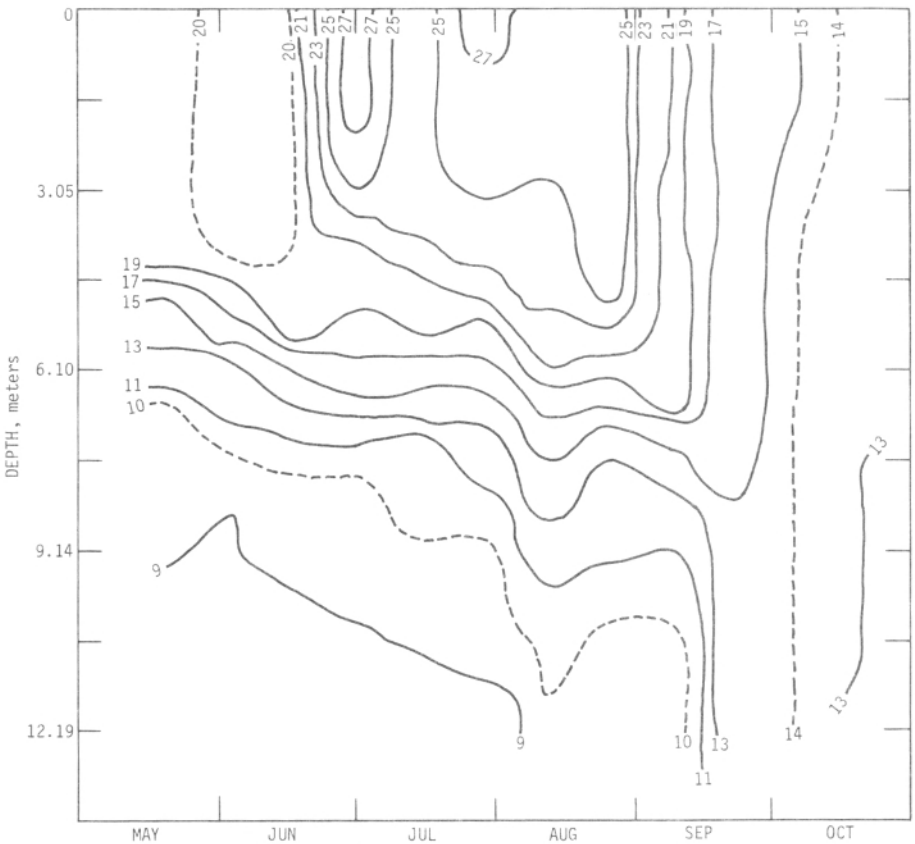

FIGURE 2.--Isothermal plots for Lake Catherine.

temperatures in the Fox Chain increased gradually reaching a maximum of about 29°C on August 4, 1975, and decreased gradually from then on. In all of the lakes, the depth of the epilimnetic zone at the time of peak stratification was found to be confined to the upper 4.6 meters.

The deep water temperatures in the lakes varied depending on the depth of the lakes. For instance, in Lake Catherine and Cedar Lake, which are the two deepest of all the lakes investigated, the water strata adjacent to the bottom ranged from 9 to 11°C during the period of summer stagnation. Deep strata water temperatures in shallower lakes were higher. Likewise, the deepest lakes destratified later than the shallow ones. Lake Catherine and Cedar Lake destratified in late September, whereas in Channel Lake, Lake Marie (west basin), and Bluff Lake the fall circulation occurred in the early part of September. This group of lakes has a maximum depth of about 9.2 meters. The phenomenon of thermal stratification was not pronounced in Lake Marie (east

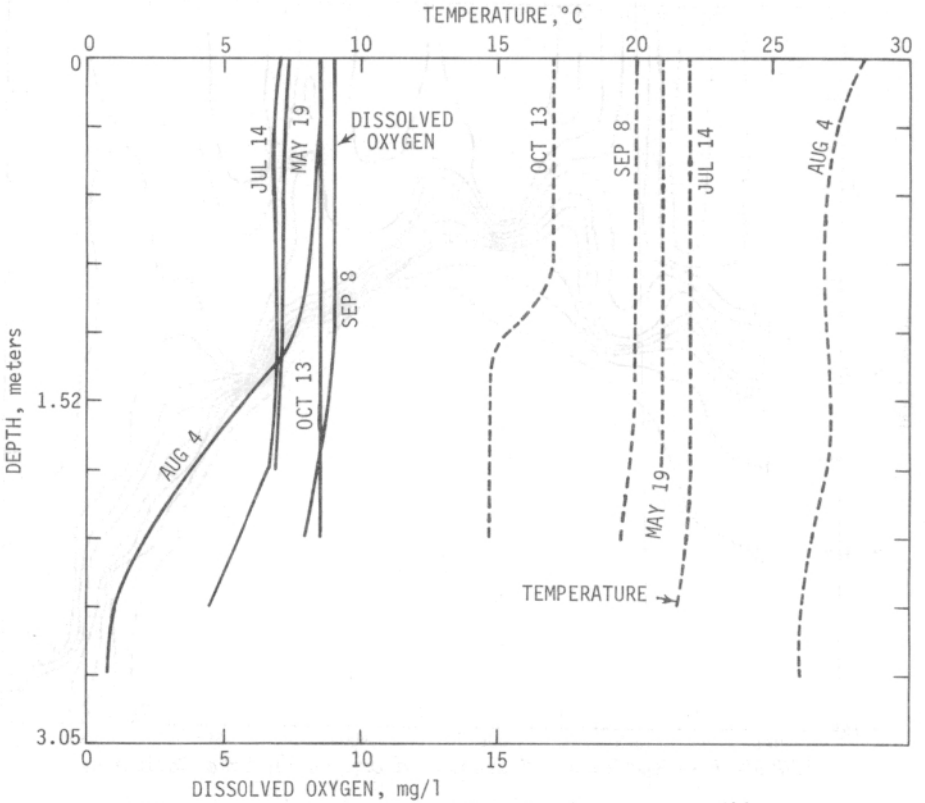

FIGURE 3.--Temperature and dissolved oxygen profiles in Fox Lake (main body).

basin) nor in Petite Lake where the maximum depths are only about 6.1 meters. In these two lakes only, a temperature gradient existed from top to bottom without any well-defined thermal stratification.

Figure 3 shows the temperature and dissolved oxygen profiles in Fox Lake, typical of shallow lakes with depths less than 3.7 meters. The temperature profiles are plotted for five different dates. The surface water temperatures reached a maximum of about 29°C on August 4. Because the lakes are shallow, they are completely mixed, both by wind action and by the intense boating activities in these lakes. Thermal gradients in these lakes are very insignificant.

On the basis of the data collected in the Fox Chain of Lakes, it can be concluded that the upper deep lakes in the Chain stratify thermally and, at the period of peak stagnation, the epilimnetic zone is only 4.6 meters deep. In the lakes with maximum observed depths of about 6.1 meters, no well-defined stratification existed. However, a perceptible degree of temperature gradient existed. In shallow lakes

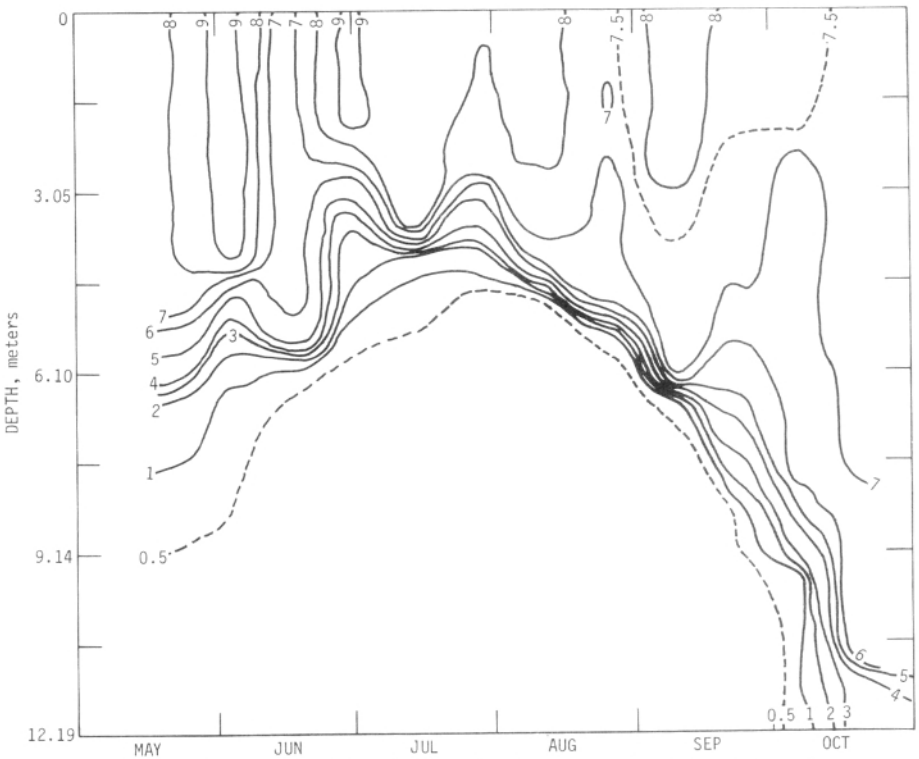

FIGURE 4.--Isopleths of dissolved oxygen in Lake Catherine.

with depths less than 4.6 meters, the entire water mass was thermally uniform.

It is common knowledge that the impoundment of water, natural or man-made, alters its physical, chemical, and biological characteristics. The literature is replete with detailed reports on the effects of impoundments on various water quality parameters. The physical changes in the configuration of the water mass following impoundment reduce reaeration rates to a small fraction of those of free flowing streams. Where the depth of impoundment is considerable, the thermal stratification acts as an effective barrier for the wind-induced mixing of the hypolimnetic zone. The oxygen transfer to the deep waters is essentially confined to the molecular diffusion transport mechanism.

The isopleth plots of dissolved oxygen for Lake Catherine are shown in Figure 4. At the beginning of the field investigation, the lake waters were anoxic from depths of approximately 9.1 to 12.2 meters. As the summer stagnation intensified, the anoxic zone of hypolimnetic waters increased progressively reaching a maximum by the end of July. The

TABLE 2. Extent of Anoxic Zones in Fox Chain of Lakes

Lake	Depth to anoxic zone from surface *(meters)*	Volume of anoxic zone *(million cubic meters)*	Percent of total volume
Catherine	4.57	1.21	39.9
Channel	4.57	1.69	31.3
Lake Marie (east and west basin)	4.57	1.02	17.4
Bluff	4.57	0.20	17.1
Pistakee Bay	3.05	1.26	41.6
Cedar	7.62		

extent of this anaerobic zone started diminishing thereafter and the dissolved oxygen concentration became uniform in the entire water column by mid-October. It must be pointed out that the progression of this anoxic zone coincided with the progression of the thermal stratification in the lake. At the time of peak thermal stratification, about 0.12 million cubic meters or 40 percent of the lake volume was devoid of oxygen. At that time, only the epilimnetic zone, about 4.6 meters deep, had acceptable levels of dissolved oxygen.

Other deep lakes in the Fox Chain of Lakes system exhibited similar trends. Even though no well-developed thermal stratification existed in Petite Lake, isopleth plots of dissolved oxygen for this lake indicate that there were periods when the water layers adjacent to the lake bottom were totally devoid of oxygen. Such episodes must have occurred during the absence of wind-induced mixing. Also in Cedar Lake, which is classified as a mesotrophic lake, hypolimnetic waters from depths below 7.6 meters were anaerobic. All the deep water samples collected from lakes with depths of 9.1 meters or more, with the exception of Cedar Lake, had a strong septic odor predominantly that of hydrogen sulfide. The maximum extent of the anoxic zones in these lakes is shown in Table 2.

Dissolved oxygen profiles for Fox Lake are also shown in Figure 3. Even though the lakes are thermally uniform, or nearly so, during the peak summer periods the oxygen demands exerted by the lake bottom sediments on the overlying waters appear to be much in excess of the oxygen replenishment from the atmosphere and algal activity. This phenomenon is much pronounced in all the shallow lakes from mid-July to mid-August, when the observed DO concentrations at 0.61 to 1.22 meters from the bottom were much less than DO concentrations in the upper layers.

Secchi Disc Observations

Secchi disc visibility is a measure of the lake water transparency or its ability to allow light transmission.

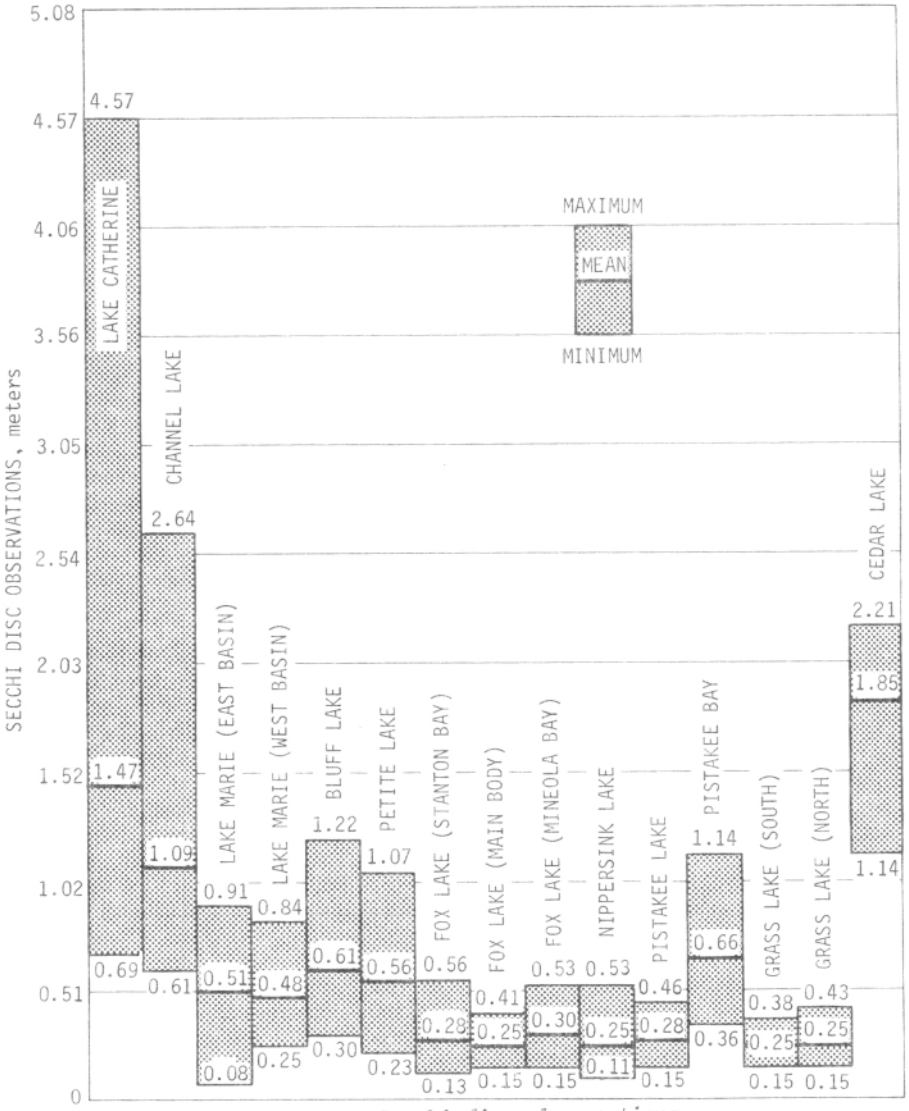

FIGURE 5.--Secchi disc observations.

The secchi disc observations in the lakes, the maximum, minimum, and mean values, are shown in Figure 5. The maximum of all the observations, 4.6 meters, was in Lake Catherine on June 3, 1975. However, Cedar Lake which is mesotrophic, exhibited the highest mean and highest minimum values. Among the Fox Chain of Lakes, Lake Catherine had the highest mean transparency value of 1.5 meters. The shallow

lakes, namely, Fox, Nippersink, Pistakee, and Grass, showed an average value of about 0.25 meter.

Figure 5 reveals that the secchi disc values are somewhat related to the maximum depth in these lakes. This suggests that the boating activities and the wind and wave actions, which could stir up the bottom sediments in shallow lakes, affect significantly the depth of light penetration. Yousef (1974), assessing the effects of boating activities on water quality in shallow lakes of Florida, has documented that agitation and mixing caused by motorboats could increase the turbidity and average particle size of suspended material through the water column.

Turbidity

High turbidity affects the aesthetic quality of the water. Its origin may be municipal and industrial wastes, clastic materials derived from a drainage basin, soil erosion resulting from agricultural practices, urban and highway developments, sediments in lakes stirred by wind, wave, and high-speed boating activities in shallow lakes, detrital remains of aquatic and terrestrial plants and animals, and algae.

Temporal variations of turbidity in two of the lakes investigated are shown in Figures 6 and 7. These figures, in addition to turbidity, show the temporal variations of all of the chemical parameters evaluated. Figures 6a, 6b, and 6c pertain to Lake Catherine surface, mid-depth, and deep water samples, respectively. These are typical of the deep lakes in the Fox Chain. Figure 7 shows the temporal variations of the parameters in Fox Lake (main body) which is typical of the shallow lakes.

The turbidity of surface and mid-depth samples of deeper lakes had relatively low values ranging from 2 to 12 FTU. The deep water samples in the Chain of Lakes exhibited high turbidity. It was most likely due to the active decomposition of the bottom sediments. The turbidity of deep water samples in Cedar Lake was relatively low, because of the low productivity of that lake.

The surface turbidities in the shallow lakes, Fox, Nippersink, Pistakee, and Grass, were much higher than surface turbidities of deeper lakes. This must be primarily due to the resuspension of bottom sediments in the shallow lakes. Grass Lake, throughout the period of this investigation, exhibited a brownish color akin to soil and humus. The other shallow lakes reflected a greenish hue during periods of algal bloom.

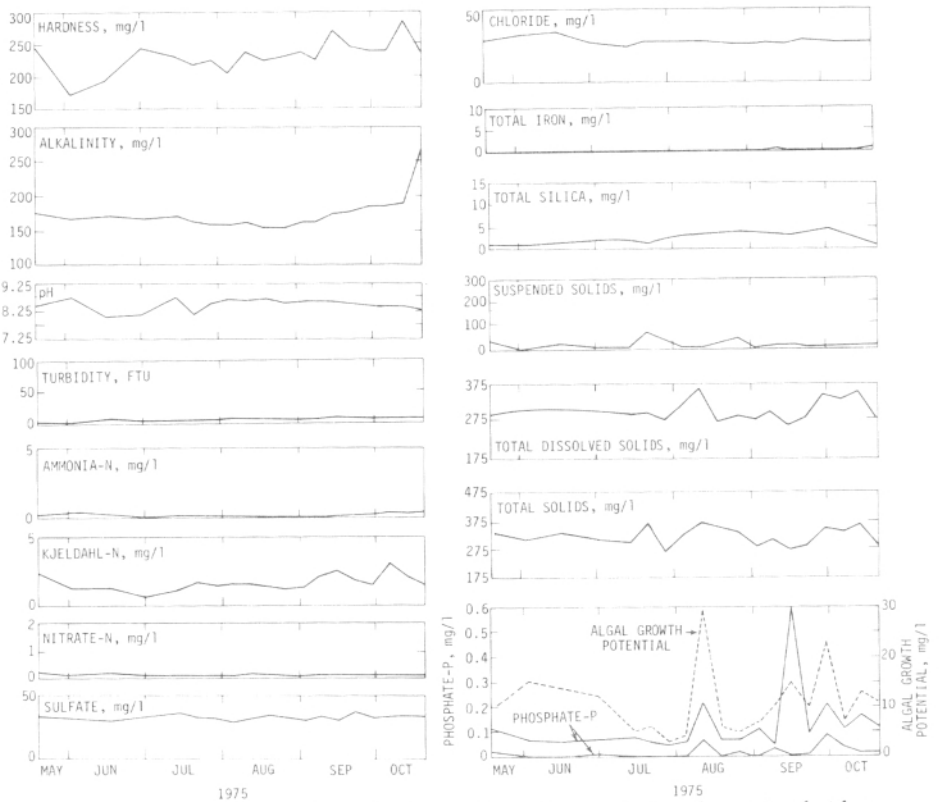

FIGURE 6a.--Temporal variations in water quality characteristics in Lake Catherine (surface).

CHEMICAL CHARACTERISTICS

pH

It is generally considered that pH values above 8.0 in natural waters are produced by a photosynthetic rate that demands more carbon dioxide than the quantities furnished by respiration and decomposition (Mackenthum, 1969). Decomposition and respiration tend to reduce pH and increase bicarbonates, whereas the tendency of photosynthesis is to raise pH and reduce bicarbonates.

As seen from Table 3, the pH values of lake surface water samples were never less than 8.0 and they generally fluctuated, with very few exceptions, in the range of 8.0 to 9.0. This is indicative of active photosynthesis in which carbon dioxide is utilized from the bicarbonate alkalinity. Bottom sediments mixed with marl, of biological origin, were found extensively in the lake system.

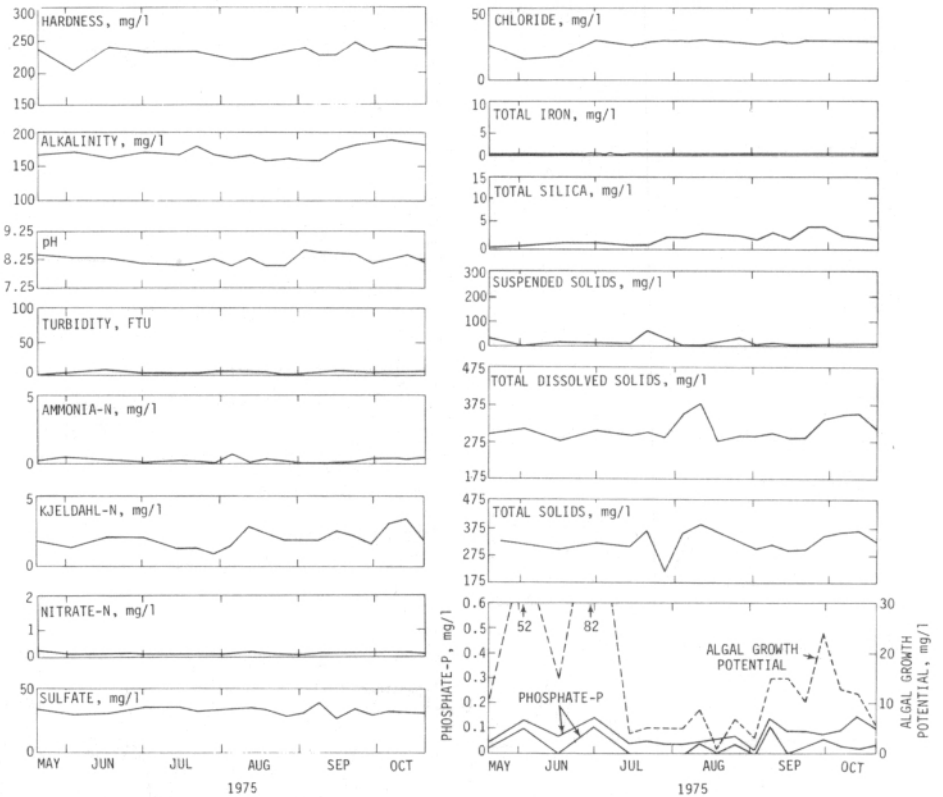

FIGURE 6b.--Temporal variations in water quality characteristics in Lake Catherine (mid-depth).

During the periods of thermal stagnation in the deep lakes, deep water samples had pH values less than 8.0 generally when the bottom sediments were undergoing anaerobic decomposition (Figure 6c). The pH values of these waters appear to increase when the lakes experience fall overturn.

Alkalinity and Hardness

These factors are governed to a large extent by the geochemistry of the watershed of the lakes. The lakes of the Fox Chain are typical of midwestern lakes, high in alkalinity and hardness. Alkalinity of the surface water samples in the Fox Chain of Lakes ranged from a low of 155 mg/l to a high of 274 mg/l. The mean alkalinity values for surface samples exhibit a spatial variation among the lakes. In the upper lakes of the Chain (Catherine, Channel, Marie, Bluff, and Petite), which are deeper than the rest, the mean alkalinity values were lower. Also

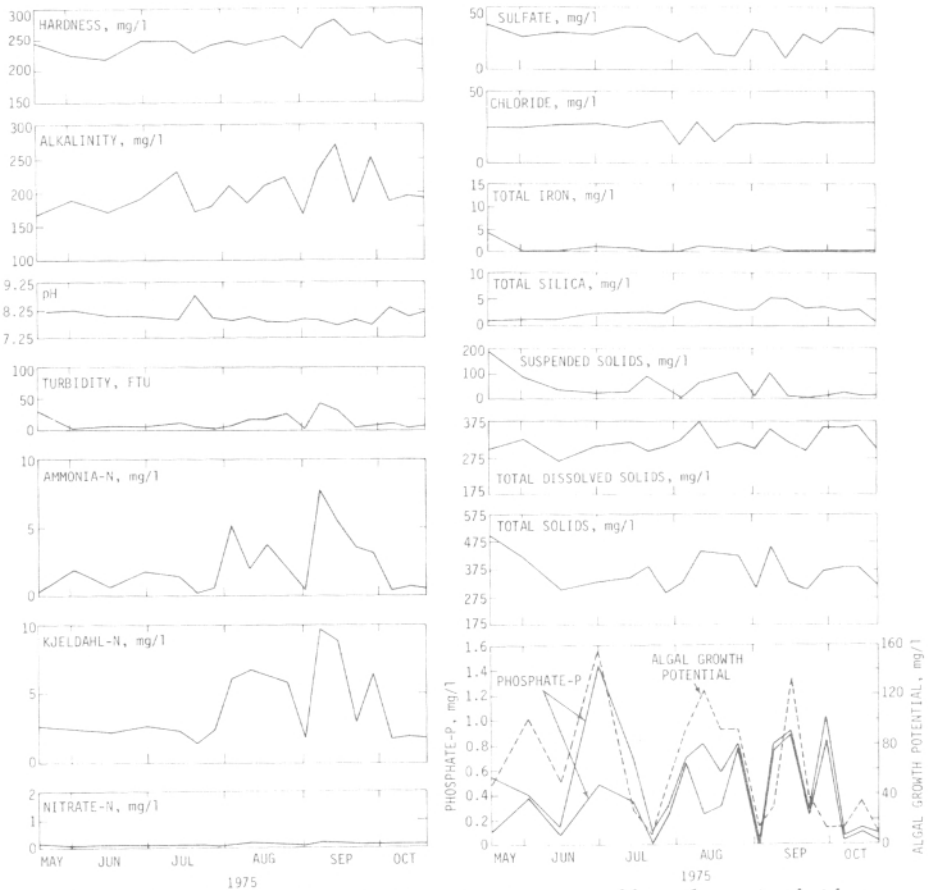

FIGURE 6c.--Temporal variations in water quality characteristics in Lake Catherine (deep).

in these lakes, the alkalinity in deep water samples are relatively higher than their corresponding surface sample values. This is true also in the case of Cedar Lake, which most of the time had the lowest of all the observed values. The temporal variations of alkalinity in the surface samples were moderate. Deep water sample variations, however, showed a noticeable peak-and-valley pattern.

The mean hardness values of surface water samples of the deep upper lakes are lower than those of the shallower lakes in the Chain. However, the differences between the surface, mid-depth, and deep values are insignificant. The hardness of Cedar Lake waters is considerably less than that of the lakes of the Fox Chain. Fluctuations of hardness values with time are much more pronounced when compared with the variations in alkalinity.

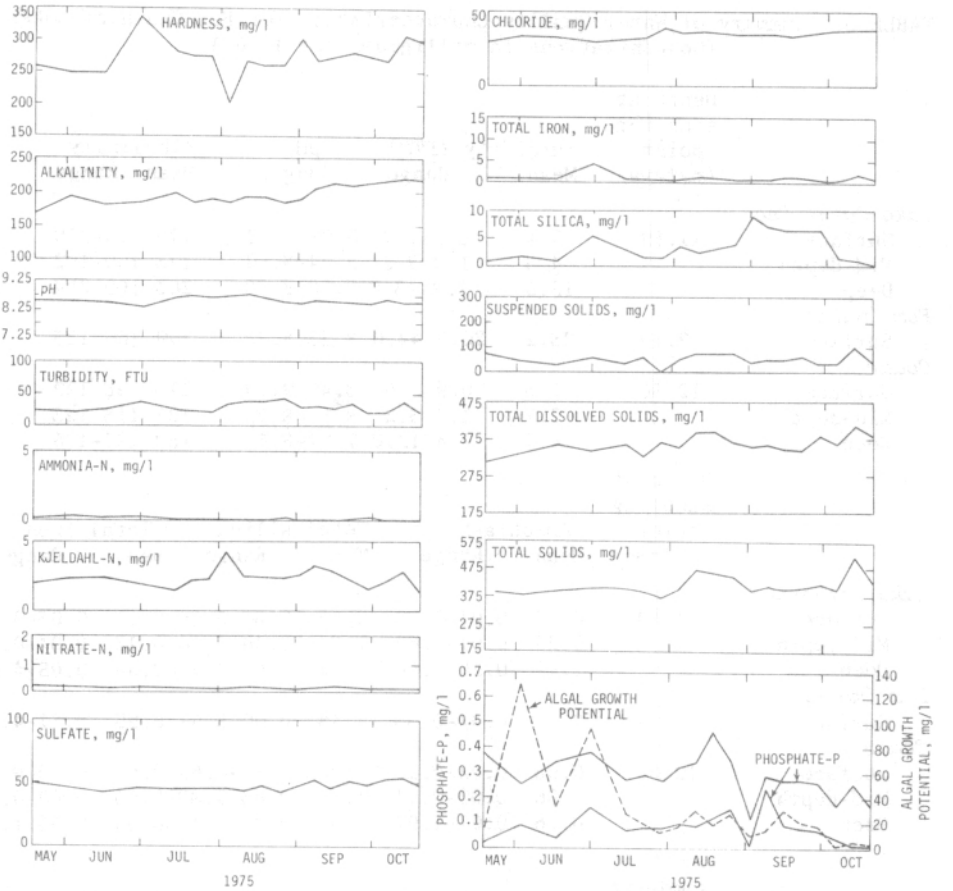

FIGURE 7.--Temporal variations in water quality characteristics in Fox Lake (main body).

Nitrogen

Nitrogen is present in water either as dissolved organic nitrogen, or as inorganic nitrogen such as ammonium, nitrate or nitrite, or as elemental nitrogen. These various forms cannot be used to the same extent by different groups of aquatic plants and algae. Nitrogen is one of the principal elemental constituents of amino acids, peptides, proteins, urea, and other organic matter.

The mean nitrate concentrations in all the lakes, including Cedar Lake, and at all the depths examined were similar. The temporal variations were also moderate. With one or two exceptions, the ranges of values for nitrate observed in all the lakes were comparable.

TABLE 3. Summary of Water Quality Characteristics for Fox Chain of Lakes (Concentrations in milligrams per liter)

	Depth at sampling point *(meters)*	Turbidity *(FTU)* Mean	Turbidity *(FTU)* Range	pH Range	Alkalinity Mean	Alkalinity Range
Lake Catherine						
Surface	11.89	5.4	2.2-7.7	8.01-8.72	176	155-270
Mid-depth		4.3	1.4-7.2	8.04-8.59	173	160-192
Deep		12.5	1.7-43.0	7.68-8.78	203	169-274
Fox (main)						
Surface	2.19	28.2	20.0-44.0	8.33-8.78	199	169-223
Cedar						
Surface	12.80	1.8	0.9-2.6	8.40-9.19	113	98-129
Mid-depth		2.1	1.4-3.2	8.15-8.79	123	118-133
Deep		4.1	1.4-12.0	7.57-8.69	160	125-196

	Depth at sampling point *(meters)*	Ammonia-N Mean	Ammonia-N Range	Total silica Mean	Total silica Range	Total iron Mean	Total iron Range
Lake Catherine							
Surface	11.89	0.15	0.01-0.39	2.23	0.80-3.76	0.11	0.03-0.30
Mid-depth		0.25	0.01-0.67	1.76	0.40-3.66	0.15	0.04-0.37
Deep		2.12	0.20-7.50	2.61	0.62-4.71	0.54	0.05-4.03
Fox (main)							
Surface	2.19	0.12	0.02-0.33	3.48	0.00-8.67	0.95	0.31-4.01
Cedar							
Surface	12.80	0.08	0.02-0.14	1.90	0.81-6.65	0.07	0.00-0.15
Mid-depth		0.06	0.02-0.11	1.62	0.43-5.88	0.06	0.00-0.09
Deep		0.96	0.01-1.94	2.59	0.00-3.47	0.60	0.06-1.70

	Depth at sampling point *(meters)*	Dissolved solids Mean	Dissolved solids Range	Suspended solids Mean	Suspended solids Range
Lake Catherine					
Surface	11.89	307	264-370	16	0-70
Mid-depth		311	278-384	14	0-62
Deep		322	268-376	47	1-202
Fox (main)					
Surface	2.19	364	316-414	53	2-105
Cedar					
Surface	12.80	212	184-242	4	1-16
Mid-depth		229	210-272	3	0-12
Deep		242	210-294	15	2-34

(Concluded on next page)

TABLE 3. Concluded
(Concentrations in milligrams per liter)

	Depth at sampling point (meters)	Hardness Mean	Hardness Range	Nitrate-N Mean	Nitrate-N Range	Kjeldahl-N Mean	Kjeldahl-N Range
Lake Catherine							
Surface	11.89	231	170-285	0.13	0.07-0.26	1.62	0.61-2.97
Mid-depth		228	200-244	0.13	0.06-0.25	1.91	0.85-3.37
Deep		242	215-278	0.12	0.06-0.19	3.81	1.35-4.57
Fox (main)							
Surface	2.19	269	196-332	0.16	0.12-0.23	2.30	1.27-4.20
Cedar							
Surface	12.80	180	156-224	0.10	0.05-0.13	1.60	0.88-2.78
Mid-depth		177	156-198	0.13	0.07-0.21	1.03	0.28-2.36
Deep		209	158-325	0.12	0.07-0.21	2.46	0.96-3.81

	Depth at sampling point (meters)	Chloride Mean	Chloride Range	Sulfate Mean	Sulfate Range	Total solids Mean	Total solids Range
Lake Catherine							
Surface	11.89	28	24-35	32	29-36	322	268-374
Mid-depth		25	14-28	33	27-40	321	214-387
Deep		25	12-29	26	8-36	367	290-502
Fox (main)							
Surface	2.19	35	30-39	48	42-55	415	372-519
Cedar							
Surface	12.80	29	25-45	23	20-27	216	185-243
Mid-depth		27	25-28	22	18-27	232	210-272
Deep		26	24-28	11	2-24	257	212-303

	Depth at sampling point (meters)	Total phosphorus Mean	Total phosphorus Range	Diss. orthophosphorus Mean	Diss. orthophosphorus Range
Lake Catherine					
Surface	11.89	0.12	0.05-0.60	0.03	0.00-0.09
Mid-depth		0.08	0.01-0.15	0.05	0.00-0.11
Deep		0.51	0.01-1.44	0.39	0.00-0.90
Fox (main)					
Surface	2.19	0.28	0.12-0.38	0.08	0.01-0.24
Cedar					
Surface	12.80	0.05	0.00-0.13	0.00	0.00-0.01
Mid-depth		0.04	0.00-0.07	0.01	0.00-0.05
Deep		0.12	0.00-0.30	0.03	0.00-0.14

In the case of deep lakes, the Kjeldahl nitrogen concentrations at surface and mid-depth were comparable to those of shallow lake surface water samples. However, the concentrations in deep water samples were nearly two to three times those observed for the surface. Increase in ammonia concentrations in the deep water zones, because of anaerobic decomposition of settled organic matter, accounts for most of the increase in the Kjeldahl nitrogen concentrations reported here. The temporal variations of ammonia and Kjeldahl nitrogen indicate that these values are much higher in deeper zones of the lake. The ammonia and organic nitrogen concentrations in deep water samples increased during the period of lake stagnation but dropped significantly as soon as the fall overturn occurred. The values of ammonia and Kjeldahl nitrogen in the surface samples of Cedar Lake were comparable to those of the deep lakes, namely, Catherine, Channel, and Marie, and Pistakee Bay. However, the values for the deep water samples in Cedar Lake were significantly less when compared with the values for the deep lakes of the Chain. This is probably indicative of the extent of organic silt accumulation and subsequent decomposition in these lakes.

Silica

The shallow lakes with the exception of Grass Lake showed higher silica concentrations than did the deeper lakes. The higher concentrations are probably associated with higher suspended solids and turbidity in these lakes. A high degree of association among these parameters has been reported in the past. The predominant algal species in Grass Lake were diatoms, constituting about 75 percent of the algal population. This could account for the lower values for silica in Grass Lake compared with the other shallow lakes in the system. The temporal variations of silica for deep waters suggest that this nutrient is released from the mud-water interface to the overyling waters during the periods of lake stagnation.

Iron

The surface sample iron concentrations in deep lakes were much lower than those in the shallow lakes. The higher concentration of iron in shallow lakes is probably associated with increased turbidity and suspended matter. Concentrations in Grass Lake are also high and comparable to other shallow lakes. Iron concentrations are significantly higher in the deep waters of the lakes. The mean and range of values observed for iron in three of the lakes are shown in Table 3.

Chloride

Chlorides are found in practically all natural waters. Chloride is a conservative element and is not directly involved in any of the physical or biological processes occurring in natural water bodies.

The mean and range of values for chloride are shown in Table 3. Except for a few abrupt fluctuations in chloride values, temporal variations appear to be insignificant. The chloride values observed in the Fox Chain of Lakes are comparable to the values found in Lake Evergreen (Kothandaraman and Evans, 1975) and in Lake Bloomington, both situated in central Illinois.

Sulfate

Sulfates occur naturally in water as a result of leaching gypsum, pyrite bearing strata, and other common minerals. Apart from the fact that sulfate exerts a cathartic effect on transient users, recommended limits on sulfate do not appear to be based on taste or physiological effects.

With the exception of Lake Catherine and Channel Lake, the mean sulfate concentrations of surface and mid-depth water samples comparable and fell within the narrow range of 43 to 50 mg/l. Sulfate concentrations in these two lakes were much lower. Cedar Lake exhibited the lowest of all values observed. Sulfate concentrations in the deep water zones were much lower than in the surface or mid-depth water samples because of the anaerobic reduction of sulfate to hydrogen sulfide as evidenced by the strong septic odor noted during the sampling of the deep water zones. The temporal variations of sulfate are relatively small in surface and mid-depth waters. There is a reduction and greater fluctuation of sulfate in the deep waters.

Total Solids, Total Dissolved Solids, and Suspended Solids

Total solids, as presented here, include total dissolved solids and suspended solids. In natural waters, the dissolved solids consist mainly of carbonates, bicarbonates, sulfates, chlorides, phosphates and nitrates of calcium, magnesium, sodium, and potassium with traces of iron, manganese, and other substances. The constituent composition of these minerals are to a large extent dependent on the geochemistry of the area contributing to the surface or groundwater resource. The amount of suspended solids found in impounded waters is small compared with the amount found in streams because solids tend to settle to the bottom in lakes. However, this aspect is greatly modified in shallow lakes by wind and wave actions and by the type and intensity of use to which these lakes are subjected.

All of the lakes in the Fox Chain except Catherine and Channel exhibited similar values of solids concentrations. Catherine and Channel exhibited values next in order of magnitude. Cedar Lake had the lowest solids concentrations of all. The total dissolved solids and suspended solids concentrations in deep waters were relatively higher than the respective values for mid-depth and surface water samples. This is essentially due to the solubilization and release to overlying waters of settled decomposing organic matter. The increased suspended matter in the

deep water samples is most likely caused by the dislodging of the sediments by the evolving gaseous by-products of anaerobic decomposition.

Phosphorus

Phosphorus is an active element which does not occur free in nature. It is found in the form of phosphates in several minerals and it is a constituent of fertile soils, plants, protoplasm, and tissues and bones of animal life. It is an essential nutrient for plant and animal growth, and like nitrogen, it passes through cycles of photosynthesis and decomposition. Phosphorus plays a vital role in the energy transfers during cell metabolism. The most important form of phosphorus for plant nutrition is ionized phosphate.

Sawyer (1952), from his experimental work with Wisconsin lakes, concluded that aquatic blooms are likely to develop in lakes during summer months when concentrations of inorganic nitrogen and inorganic phosphorus are in excess of 0.3 mg/l and 0.01 mg/l, respectively. These critical levels for nitrogen and phosphorus concentrations have been accepted and widely quoted in scientific literature. Numerous published reports indicate that productivity is largely determined by two factors, i.e., phosphorus and nitrogen. Phosphorus is predominant over nitrogen as a limiting factor.

The mean and range of values for phosphorus concentrations in the Fox Chain of Lakes and Cedar Lake are shown in Table 3. From the data presented, it is seen that the mean dissolved orthophosphorus concentrations in Cedar Lake are much less than the values observed in the Fox Chain of Lakes. Characteristically, the dissolved orthophosphorus concentrations in the deep water zones were found to be several orders of magnitude higher than the values determined for surface and mid-depth water samples in these lakes. This was true in the case of Cedar Lake also. However, a comparison of the mean dissolved orthophosphorus concentrations in the deep water samples indicates that concentrations in the Fox Chain of Lakes are 10 to 25 times the value observed for Cedar Lake. The mean orthophosphorus concentrations in the surface and mid-depth samples were 0.00 and 0.01 milligrams per liter, respectively. The orthophosphorus concentrations in the surface and mid-depth samples in the Fox Chain of Lakes were higher than the critical levels of phosphorus concentration suggested by Sawyer (1952). The orthophosphorus concentrations observed in deep zones of the Fox Lakes were about 40 to 75 times higher than the critical level.

Considering the phosphorus concentrations, and the algal densities observed in the Fox Chain of Lakes and Cedar Lake, it can be concluded that phosphorus is the key element in the eutrophic condition of the Fox Chain of Lakes. The nitrate-nitrogen concentrations in all of the lakes including the deep water zones were comparable. Ammonia concentrations were higher in the hypolimnetic zones of the deep lakes. Phosphorus appears to be the most critical of the two nutrients.

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