ISWS/CIR-139/79
Circular 139
STATE OF ILLINOIS
ILLINOIS INSTITUTE OF NATURAL RESOURCES

Effect of Bottom Conditions on Eutrophy of Impoundments

by D. P. ROSEBOOM, R. L. EVANS, W. WANG,
T. A. BUTTS, and R. M. TWAIT

ILLINOIS STATE WATER SURVEY
URBANA
1979

CONTENTS

Printed by Authority of the State of Illinois
(9-79-1000)
[P.O. 16609]

Effect of Bottom Conditions on Eutrophy of Impoundments

by D. P. Roseboom, R. L Evans, W. Wang,
T. A. Butts, and R. M. Twait

ABSTRACT

Two man-made impoundments, Lakes Eureka and Canton in central Illinois, were studied to develop procedures for assessing behavior characteristics and thereby relative eutrophy of waters in man-made lakes, as opposed to traditional assessments of glacial lakes. Likenesses and differences for the two lakes in productivity, water chemistry, and sediment oxygen demand were identified.

Both lakes are used for public water supply and recreation. Both thermally stratify and maintain an anerobic zone in bottom strata for a 5-month period in summer; stratification is weak in the shallower Lake Eureka, but well defined in Lake Canton. The rate of anerobic zone formation is greater in Lake Eureka but the zone's extent from the bottom is less than in Lake Canton; overall, oxygen depletion conditions in Lake Canton are the most severe. The thermal stratification of the lakes is not a barrier to the extent the anerobic zone penetrates the overlying waters.

Both lakes support blue-green algae blooms. The density of algae at Lake Canton exceeds that at Lake Eureka; however, alkalinity reductions at the surface indicate algal productivity of Lake Eureka exceeds that of Lake Canton by 30 percent, and alkalinity increases in the bottom waters indicate microbial activity in bottom muds in Lake Eureka exceeds that in Lake Canton by 44 percent. Differences in alkalinity between the surface and bottom waters in both lakes were significant. Nonetheless, higher total and dissolved phosphorus contents in Lake Canton bottom waters give that lake a greater potential for productivity; overall, Lake Canton can expect more problems with nuisance algal blooms than Lake Eureka.

Significant quantities of iron and manganese (mainly Fe^{++} and Mn^{++} forms) are released from the bottom muds of both lakes during summer stagnation. Migration of iron and manganese up the water column is limited to the vertical extent of the anerobic zone. Similarly, significant ammonia-nitrogen produced in the bottom waters is limited to vertical extent of the anaerobic zone; the oxygen demand potential of ammonia-nitrogen may be a major influence on the extent and duration of the anaerobic zone. Chlorine demand of bottom waters is greater than that in upper water layers in both lakes. Ferrous iron was the principal component of chlorine demand in Lake Eureka; sulfides imposed the principal demand at Lake Canton.

Unexpected problems with gas production required developing new equipment for *in-situ* sediment oxygen demand (SOD) measurements, leaving time for only a few successful collections. A method using SOD rates is given for predicting the rate of ascent of DO-depleted water in a water column during development of an anaerobic zone. Also given is a laboratory batch method using BOD bottles for determining relative rates of SOD in lake muds. SOD rates were less for Lake Eureka than for Lake Canton. The density and taxa of benthic macroinvertebrates were similar to those from anaerobic zones in other Illinois lakes. The relative eutrophy of the lakes determined mainly by bottom conditions indicates worse conditions in Lake Canton than in Lake Eureka; water depth may govern the extent and duration of the anaerobic zone. More precise and less time consuming measurement techniques are needed.

INTRODUCTION

The utility and value of lake systems as vital components of Illinois water resources has gained recognition in recent years. This interest has led to increasing concern about conditions of water quality in the lakes. As this attention broadens and state agencies become more committed to an active role in lake management, rational methods for identifying the relative eutrophy of waters in publicly owned lakes in Illinois will be needed. The methods will permit development of a classification system that will be useful in establishing priorities for lake management schemes.

Several states have already formulated classification systems. Notable among these systems are the Lake Condition Index and the Trophic Status Index designed for Wisconsin conditions. The systems being used generally incorporate some of the following measurements and assessments for evaluative purposes:

1 Transparency
2 Organic nitrogen
3 Dissolved phosphorus
4 Chlorophyll a
5 Planktonic biomass
6 Dissolved oxygen
7 Inorganic nitrogen
8 Temperature
9 Detention time
10 Nuisance algae
11 Excessive macrophytes
12 Fish kill occurrences
13 Recreation impairment
14 Pollution problems

The use of measurements 1 through 10 for comparing lake conditions has been fostered from observations of the behavior of glacial lake systems. However, the inland glacial lake systems in Illinois are generally confined to the two northeastern counties of Lake and Henry, and most lakes in Illinois are man-made impoundments. It has been suggested that man-made impoundments should be considered very wide slow moving rivers and not lakes at all. The major point is that the behavior of glacial lakes and man-made impoundments differs and the unqualified application of principles derived from studies of glacial lakes to man-made impoundments is questionable.

For example, the students of glacial lake systems consider the reduction of dissolved oxygen in the lower water strata (hypolimnion) an indicator of the aging process of a lake brought about by increasing productivity of the overlying waters. Observations of man-made impoundments, with water depths of 15 feet or more, indicate that the hypolimnion during summer months is devoid of oxygen from the time of the lake's creation. Under these conditions, the quantity of dissolved oxygen in the hypolimnion of man-made impoundments cannot be relied upon for classification purposes.

A similar problem arises in using water transparency measurements. In glacial lakes and in some man-made impoundments, the transparency of a lake's water is a bonafide indicator of trophic status. It is based on the assumption that the magnitude of organic production, mainly algal cells, affects the color and turbidity of the water thus influencing its transparency. More frequently the transparency of man-made impoundments in Illinois is a function of inorganic material (silt, clay) with little relationship to organic production except to discourage it.

The study reported here is a summary of initial efforts to develop procedures for confidently assessing some of the behavior characteristics of man-made impoundments.

Study Area

Two man-made impoundments, Lakes Eureka and Canton, were chosen for examination. Lake Eureka in Woodford County was created in 1942. Lake Canton in Fulton County was created in 1939. During the study both impoundments were the source of public water supply for the communities from which their names were derived, the cities of Eureka and Canton. Soon after completion of the study, the city of Eureka converted to groundwater as a public water supply.

In addition to being sources of water supplies the lakes are also used for recreation. A more detailed description of the lakes and their environs will be presented in a later section.

Objectives and Scope

The overall objective of the study was to employ and develop techniques that could be used to measure the sources of significant oxygen demand and the rates of dissolved oxygen reduction within the waters of the lakes. It was assumed that the major sources of oxygen demand are the lake bottoms and their by-products.

The *in-situ* rates of oxygen reduction within the water column and bottom water strata were determined by measuring the concentrations of hypolimnetic oxygen during the formation of the anaerobic zone within each lake. The influencial by-products of the bottom were deemed to be iron, manganese, phosphorus, and ammonia. Temporal measurements were performed to determine their concentrations within the water column. Chlorine demand analyses were performed also as an indirect measurement of inorganic reductants and other oxidizable material in the water column. For characterizing bottom sediments, analyses were performed for organic and moisture content as well as iron and manganese concentrations. *In-situ* measurements for sediment oxygen demand were undertaken and a technique for performing sediment oxygen demand measurements in the laboratory was developed. Other analyses associated with the influence of the lakes' bottoms as well as their surface waters included alkalinity and pH. Water temperatures in all cases were recorded.

In essence the questions pursued were: Are there identifiable changes in the water quality of man-made impoundments that are clearly associated with the characteristics of bottom sediments? Are the characteristics of bottom sediments and their associated by-products so singularly distinguishable that they may be used for classifying lake systems?

Methods

The collection of samples, subsequent analyses, field measurements, and observations were performed at the two lakes during the period April through October 1978. Samples were collected and measurements were made at a single station located at the deepest portion of each lake. The station water depth was about 18 feet at Lake Eureka and about 32 feet at Lake Canton, both at crest elevation. The methods used for field measurements, sampling, and analyses are as follows.

Transparency, Dissolved Oxygen, and Temperature. An 8-inch diameter secchi disc with black and white quadrant markings attached to a calibrated line was used to measure water transparencies. 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. Again, the depth of immersion was noted. The average of the 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 57, with a 50-foot probe lead was used. At each lake, often at several depths, the probe was standardized in lake water in which the dissolved oxygen content was determined by a modified

Winkler Method as outlined by the American Public Health Association (1975). Temperature and dissolved oxygen measurements were obtained at 1-foot intervals starting from the water surface.

Alkalinity and pH. On each visit to the lakes, alkalinity and pH samples were obtained with a Kemmerer water sampler at the surface, at the lowest water depth, and wherever the DO concentration in the water column first dropped to zero. Analyses were performed that same day on the water samples with a portable Metrohm-Herisau pH meter (Model E588). The alkalinity was titrated on a 50-ml sample to a pH of 4.5 with 0.020 N H_2SO_4.

Iron and Manganese. Samples for iron and manganese analyses were collected at varying depths in the water column, at the interface of the bottom, and from the bottom sediments. A Juday sampler was used for water column collections. The sampler permits selective collection of a water sample and is sufficiently flushed by the water collected to allow transport of the sample and subsequent analyses without the influence of oxygenation. The interface sample was obtained 3 cm above the sediment by a modification of the device developed by Sullivan (1967). The sediment samples were collected with an Ekman dredge.

The water samples (approximately 300-ml volume) were acidified in the field with 2 ml of concentrated hydrochloric acid. The samples were allowed to settle, and supernatant was withdrawn for analyses. Determinations were made for *soluble* ferrous iron, *soluble* total iron, and manganese. Ferrous iron determinations were made by the phenanthroline method described in *Standard Methods* (American Public Health Association, 1975). Total *soluble* iron and manganese determinations were performed by atomic absorption spectroscopy. The interface samples were also acidified in the field and the same analytical procedures were applied to them as described for the water samples. Total iron and manganese measurements in the sediments were determined by atomic absorption spectroscopy.

Ammonia. Samples for ammonia analyses were collected with a Juday sampler and an interface sampler at varying depths as described for iron and manganese. Special handling, in the field,was provided for the samples. A 50-ml portion of the Juday and interface water samples was filtered through type HA, 0.45 μm millipore filters 37 mm in diameter. The filters were placed on filter pads which were held between circular holders. 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. This method of sample preservation is considered superior to acidification or other chemical additives.

Phosphorus. Water samples for phosphorus analyses were collected with a Kemmerer sampler at the water surface, at mid-depth, and near the bottom. Analyses were made for total and dissolved phosphorus. Determinations for dissolved phosphorus were performed on the sample after filtering through a 0.45 μm membrane filter.

Chlorine Demand. Samples for chlorine demand analyses were the same as those collected for phosphorus determinations. A 200-ml sample was dosed with a chlorine solution to provide an initial chlorine residual concentration of 12 to 15 mg/1. After a contact period of 30 minutes at room temperature the residual chlorine concentration of the sample was determined. The difference between the initial chlorine concentration and the residual concentration after 30 minutes was considered the chlorine demand of the sample.

Moisture and Volatile Content. The sediment samples were examined for moisture and volatile content. To determine moisture content the sediment sample was decanted after storage for about 16 hours under refrigerated conditions. The sample residue was thoroughly mixed and a portion oven dried at 103° C. The loss of moisture was expressed as a percentage of the original wet weight. The sample was then analyzed for volatile (organic) content using a muffle furnace at 600° C as described in *Standard Methods* (American Public Health Association, 1975).

Table 1. Analytical Procedures

Water transparency	Secchi disc
Dissolved oxygen	Oxygen meter
Temperature	Thermister
Alkalinity	Potentiometric Method
pH	Glass electrode method with portable Metrohm-Herisau meter (model E588)
Soluble ferrous iron	Phenanthroline
Total soluble iron	Atomic absorption
Total soluble manganese	Atomic absorption
Total iron and manganese (sediments)	Atomic absorption
Ammonia	Phenate Method
Phosphorus	Ascorbic acid Method
Chlorine residual	Iodometric Method I
Sediment moisture and volatile content	Evaporation at 103°C and ignition at 600°C

Table 1 describes the analytical methods used for physical measurements and chemical concentrations. Methodologies for *in-situ* and laboratory sediment oxygen demand measurements, benthic organism collections, and oxygen demand of the lake waters will be discussed in the section on Lake Sediment Data Reduction.

Plan of Report

Three basic sections are presented. The first section is an evaluation of the elements examined in the waters of the lakes. The second section deals with a similar scrutiny of the elements investigated in the bottom sediments of the lakes. A summary follows each element evaluated. The third section presents the conclusions. The material presented here has been reported in "Classifying Illinois Impoundments: An Examination of Techniques for Assessing Lake Bottom Conditions" prepared for and funded by the Illinois Environmental Protection Agency (Roseboom et al., 1979). Original data are presented in the appendix of that document.

Acknowledgments

This investigation was performed under the general supervision and guidance of Dr. William C. Ackermann, Chief of the Illinois State Water Survey. Illustrations were prepared by William Motherway, Jr. Miss Linda Johnson typed the original manuscript; Mrs. J. Loreena Ivens and Mrs. Patricia A. Motherway edited the final report; and Mrs. Marilyn Innes prepared the camera copy.

The authors are indebted to many persons for technical assistance and advice during the course of this study. Kenneth Rogers of the Illinois Environmental Protection Agency provided the liaison to insure proper funding and contractual arrangements; Orval Kuhn, Superintendent of Water Treatment at Canton, and Berny Arbuckle, Director of Public Works at Eureka, were most helpful in providing access to the lakes. Many Survey personnel participated in analytical determinations and biological identifications: Dave Hullinger and Dana Shackleford performed chemical analyses, Dave Beuscher identified and enumerated algal collections, and Tom Hill and Scott Bell examined benthic collections. Without the professional understanding and willing cooperation of these persons, the investigation would not have been completed.

LAKE WATER DATA REDUCTION

Lake Eureka and Lake Canton, located about 40 miles apart, were constructed principally as sources for public water supplies. Lake Eureka was formed in 1942 by damming a branch of Walnut Creek. Lake Canton began to fill in 1939 after the impoundment of Copperas Creek. Both lakes have the typical serpentine shape of midwestern impoundments as shown in figures 1 and 2. The morphometric details for each lake are given in table 2. Lake Eureka, the smaller of the two, has an average water depth of about 6 feet. Lake Canton's average water depth is 14 feet.

A sampling station for each lake is located in the deeper portion near the dam. At these stations the average water depth during summer months was 16 feet and 31 feet, respectively, for Lake Eureka and Lake Canton. It has been the experience of the State Water Survey, from observations of other man-made impoundments in Illinois, that the selection of a single station in the deep portion of an impoundment is sufficient to adequately define the temperature and dissolved oxygen regimes.

Transects of the two sampling stations are shown in figures 3 and 4, along with transects of other sectors of the lakes (locations on figures 1 and 2). These transects give an idea of the areal expanse of water in each lake in relation to its water depth. Details of these relationships for Lakes Eureka and Canton are shown, respectively, in figures 5 and 6.

As mentioned earlier, measurements and sampling at the lakes were performed from April through October 1978. Except for sample collections for chlorine demand and phosphorus determinations, which were done on a weekly interval, sampling and measurements were not performed at any fixed interval of time but were contingent upon the behavior or expectations thereof of the lakes' waters. The following is a summary of the effort.

	Number of visits	
	Lake Eureka	*Lake Canton*
Water transparency	48	57
Temperature versus depth	73	83
Dissolved oxygen versus depth	73	83
Alkalinity at 3 depths	50	57
pH at 3 depths	50	57
Iron, manganese, and ammonia at varying depths	20	22
Phosphorus and chlorine demand at varying depths	25	27
Sediment organic and volatile content	8	8

The following discussion sets forth an evaluation of the pertinent water quality data obtained during the study.

Table 2. Pertinent Physical Data

	Lake Eureka	*Lake Canton*
Storage, *acre-feet*	227	3025
Surface area, *acres*	36	218
Mean depth, *feet*	6.3	13.8
Maximum depth, *feet*	18	32
Mean depth: Maximum depth	0.35	0.43
Watershed area, *acres*	1700	9500

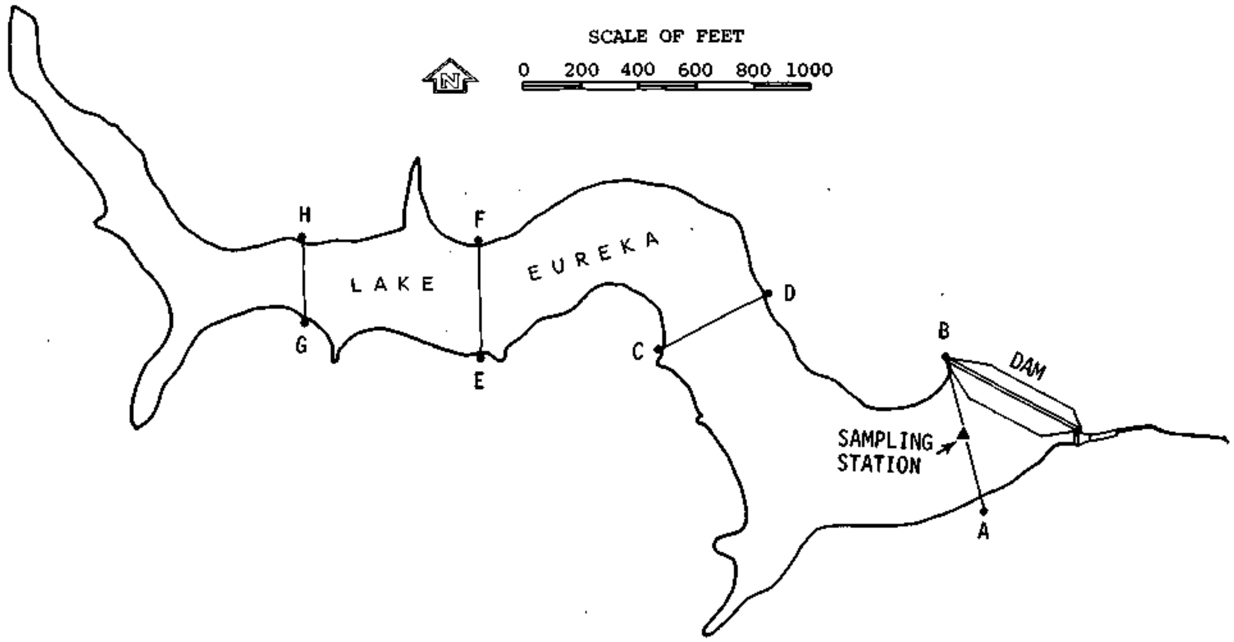


Figure 1. Plan view, Lake Eureka

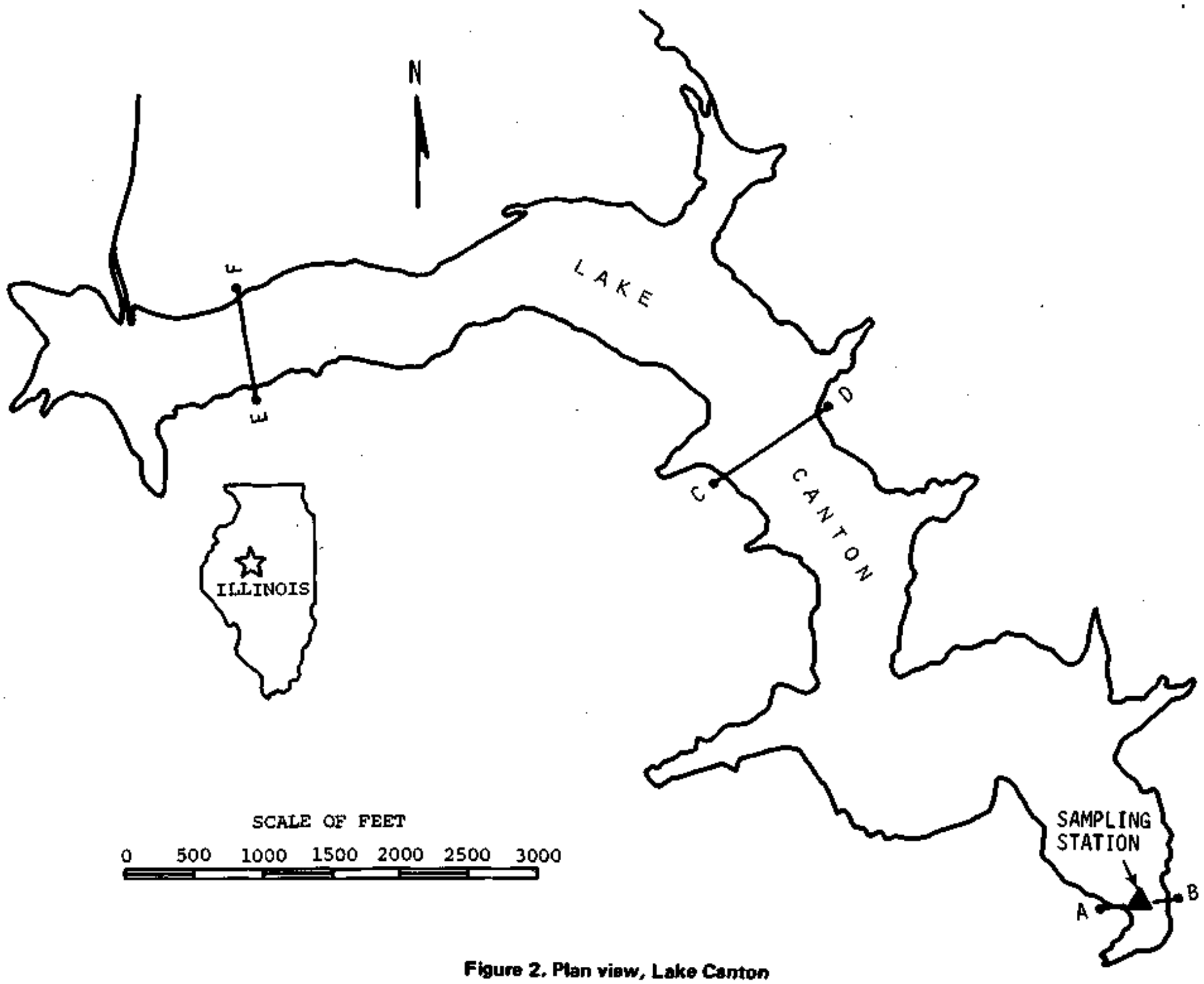


Figure 2. Plan view, Lake Canton

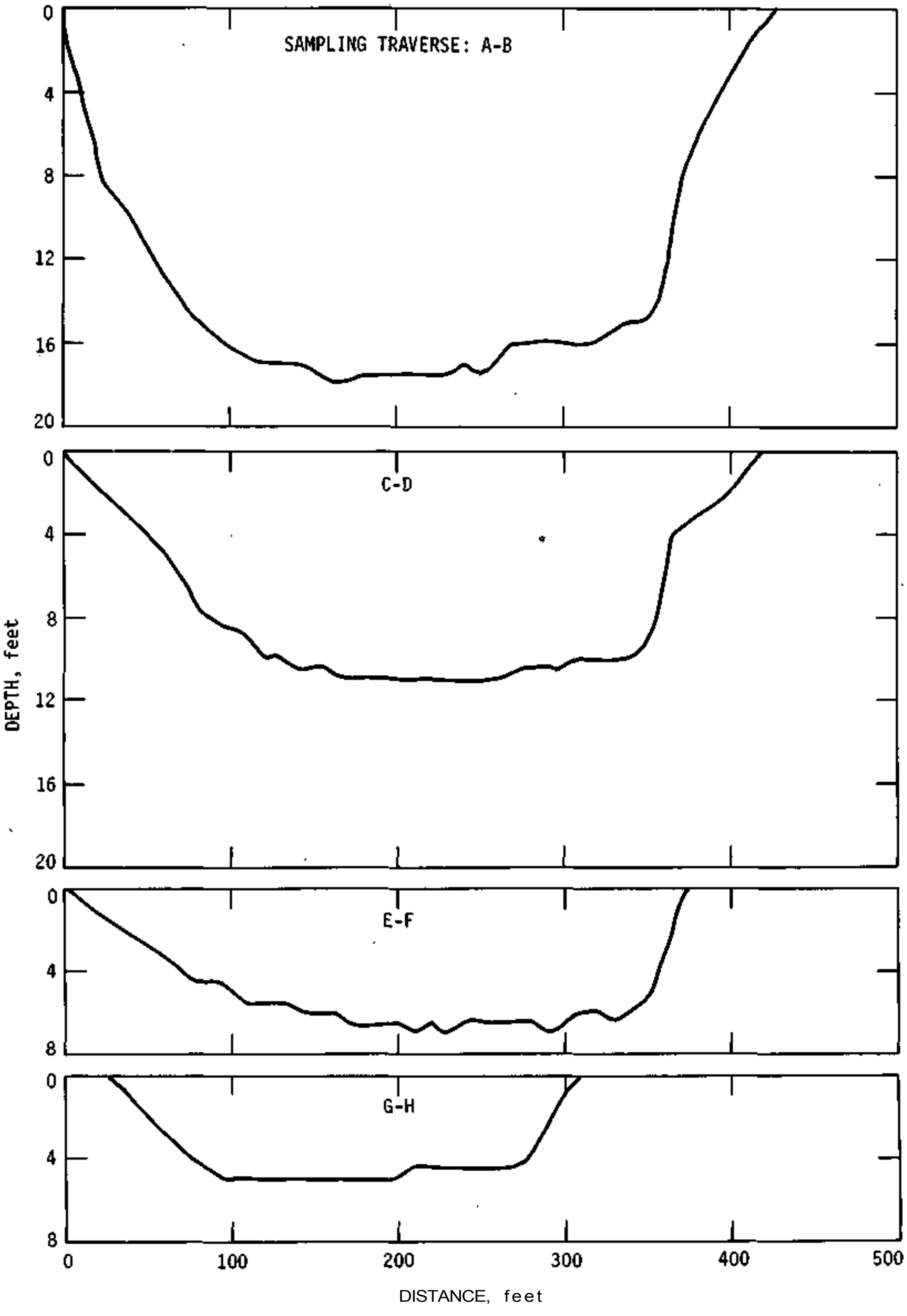


Figure 3. Transects of sampling stations. Lake Eureka

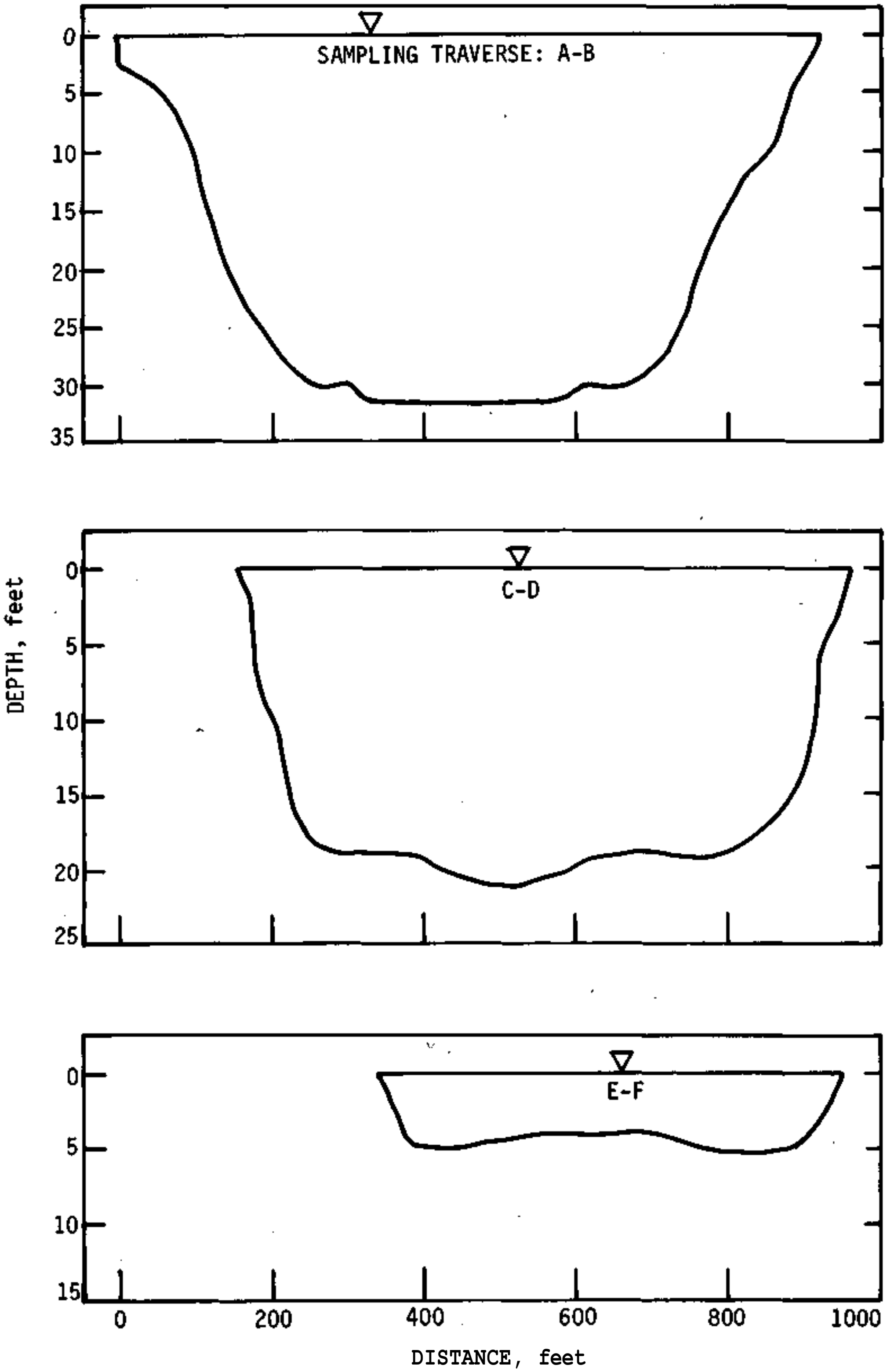


Figure 4. Transects of sampling stations. Lake Canton

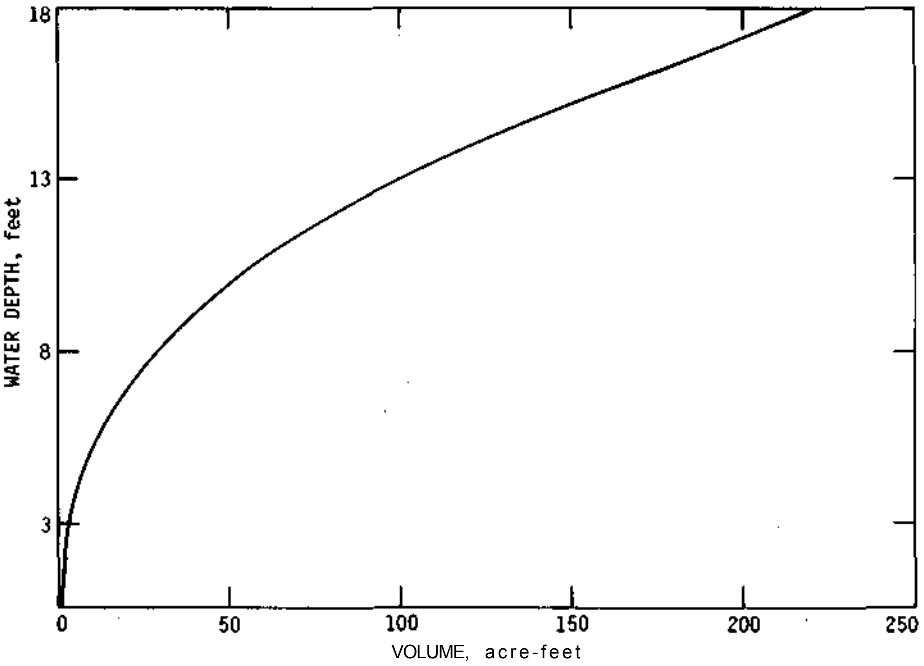


Figure S. Depth-volume relationships. Lake Eureka

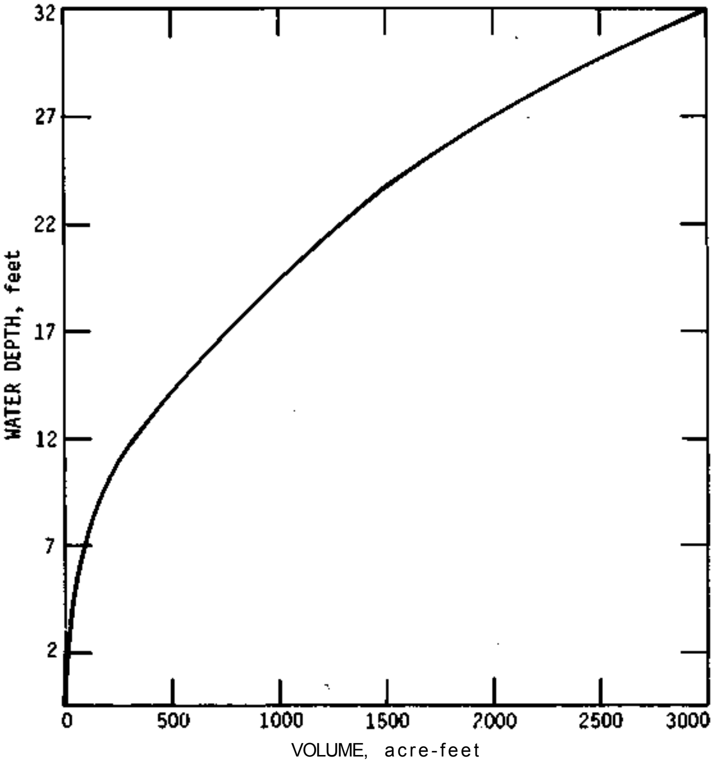


Figure 6. Depth-volume relationships. Lake Canton

Transparency

The transparency of a lake's water, as measured by secchi disc observations, is an estimate of the waters ability to allow light transmission at the water surface. Transparency is related to water color, suspended sediment consisting of silt and clay, and algal density. The clarity of surface water at Lake Eureka during this study is shown in figure 7. On the average it varied from 25 to 45 inches. On two dates of measurement the transparency exceeded 45 inches. During May and August 1978 the water clarity was generally less than 25 inches. The limitation during May was probably caused by inorganic suspended sediment; during August water clarity was probably governed by algal densities. A minimum value of 12 inches occurred on August 10. A maximum recorded transparency of 68 inches occurred on July 7.

At Lake Canton the water transparency, on the average, varied from 40 to 80 inches (figure 8). During extended periods of May and August and all of September the water clarity did not exceed 25 inches. As in the case of Lake Eureka, the diminishment of transparency in May was probably caused by suspended clay and silt particles. The lack of clarity in August and September was due to algal densities. A minimum value of 15 inches occurred on August 14; maximum water clarity of 86 inches was recorded on June 20 and 26.

During this study, Lin (1978) developed data regarding algal densities at the water surface of both lakes, as shown in figure 9. The insignificant algal growth during May justifies the assumption that minimum water clarity in the lakes at that time was caused by substances other than algae. However, a substantial increase in algal densities did occur in Lake Eureka (2000 to 2700 counts/ml) in early August causing the minimum transparency measurements during that month. Substantial pulses of algal growth occurred in Lake Canton during early August, mid-August, and early September (3100 to 4000 counts/ml) thus lessening water clarity during those months.

The instability of secchi disc measurements as depicted in figures 7 and 8 suggests the difficulty of relying on such measurements to classify lakes in Illinois. To do so would require several years of record involving at least 50 to 70 observations per year for the period April through October.

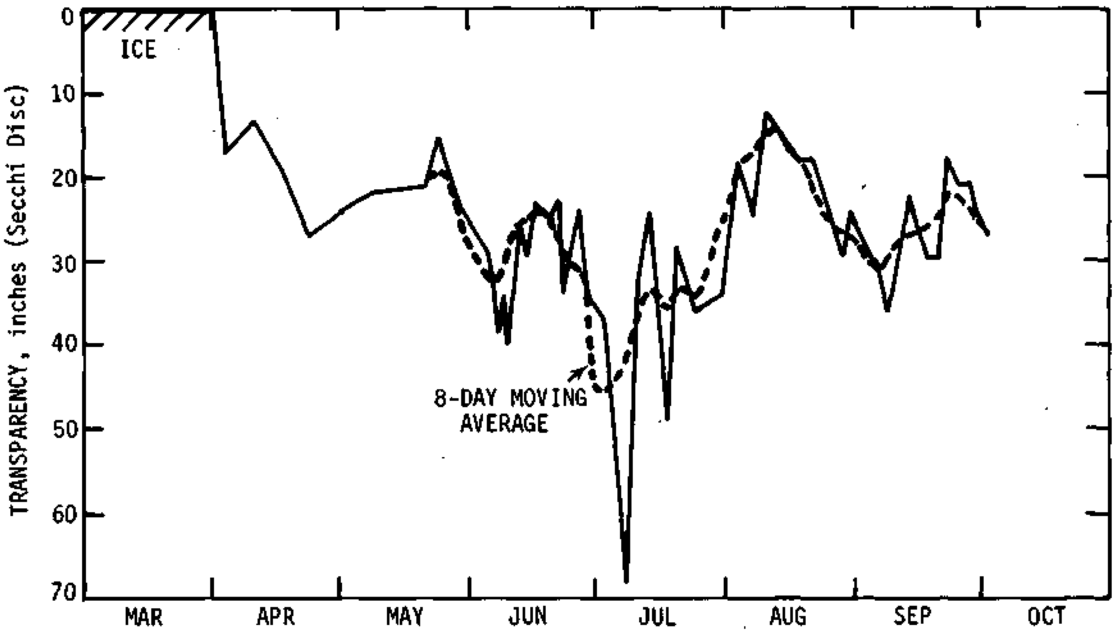
Without the influence of algae, the surface waters of Lake Canton are more transparent than those of Lake Eureka. This is likely because Lake Eureka is a shallower lake which permits more interaction of the overlying water with the lake bottom. At lake-full conditions about 54 percent of the water volume overlies the bottom at depths of 5 feet or less. Under similar conditions at Lake Canton only 33 percent of the water volume is 5 feet or less in depth.

In summary:

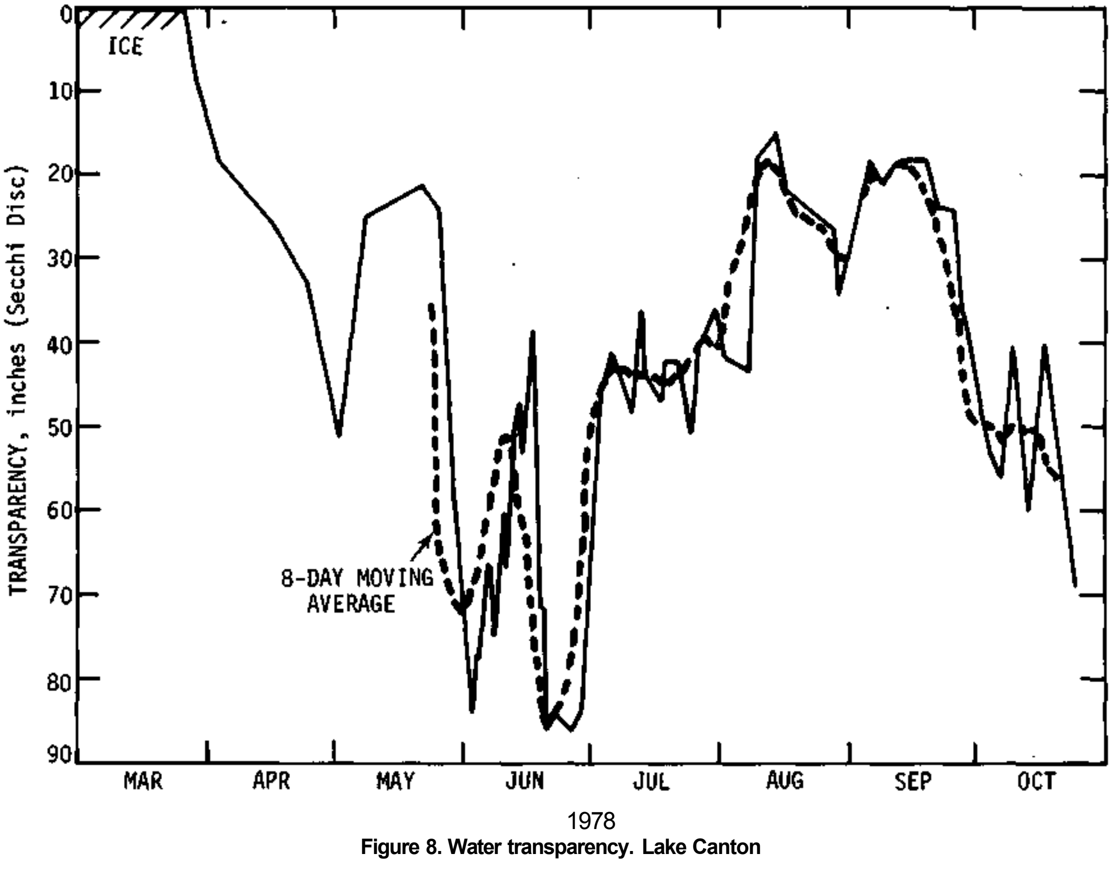
- The transparency of Lake Eureka waters, on the average, varied from 25 to 45 inches. That for Lake Canton on the average varied from 40 to 80 inches.
- Minimum water clarity occurs in late spring and late summer in the two lakes. During the spring months clarity is regulated by inorganic suspended sediment; in late summer it is influenced by algal densities.
- The waters of Lake Canton are more transparent than those of Lake Eureka. This is likely a function of the relative water depths of the two lakes.

Temperature

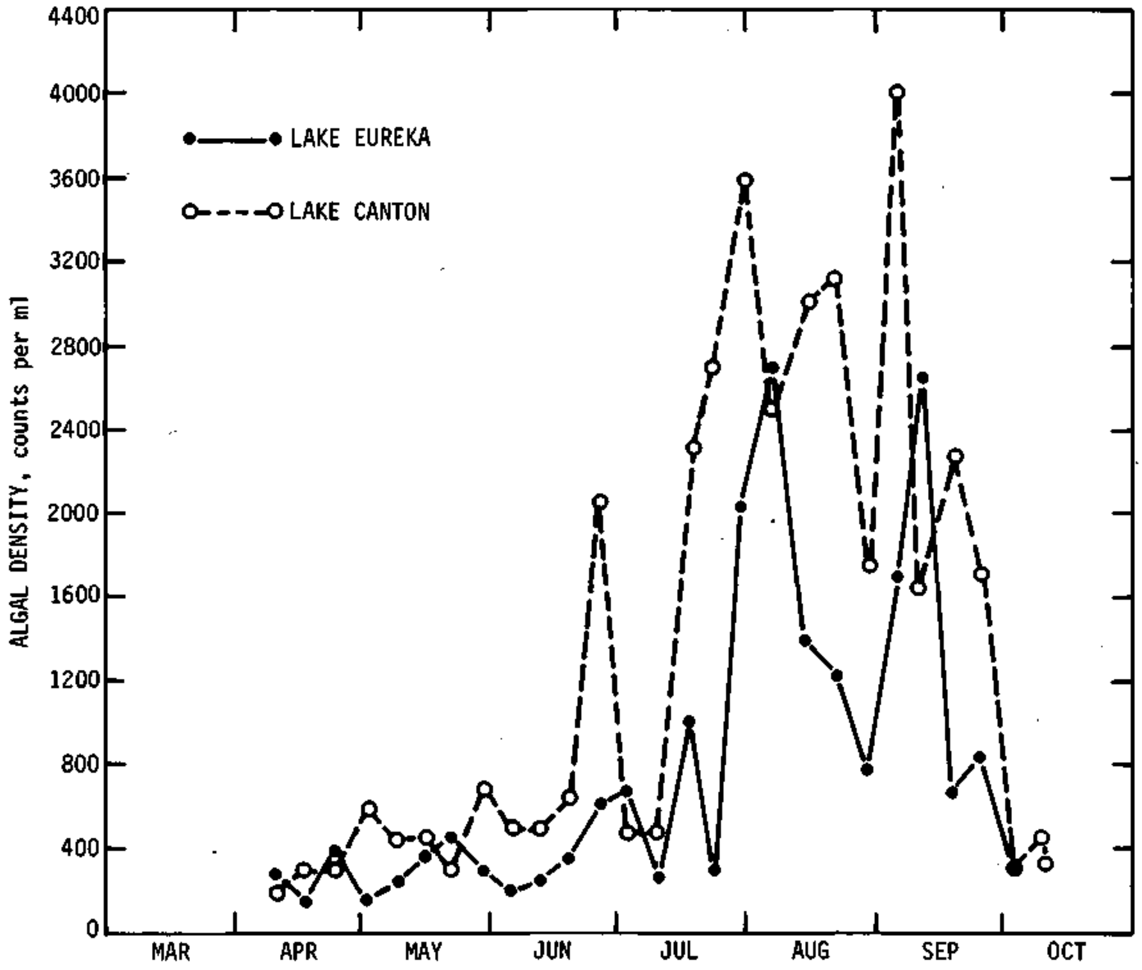
Lakes in Illinois generally undergo seasonal temperature changes throughout the water column. In winter, especially during ice cover, the temperature of the bottom waters is about 4° C.



1978
Figure 7. Water transparency. Lake Eureka



1978
Figure 8. Water transparency. Lake Canton



1978
Figure 9. Algal densities at water surface. Lakes Eureka and Canton

Exceptions occur when groundwater intrusion is substantial; under these conditions bottom waters may not become cooler than 10° C. As air temperatures rise, the upper layers of water warm up and mix with the lower layers by wind action. By late spring, the rate of temperature increase in the upper layers of water exceeds that in the lower layers and the waters of the lake become thermally stratified.

Thermal stratification usually occurs in Illinois lakes when water depths exceed 15 to 18 feet. However, there are exceptions. In those lakes where a substantial expanse of surface water is exposed to the prevailing summer winds, thermal stratification may not occur. Rend Lake (maximum depth 31 feet) in Franklin and Jefferson Counties, and Lake Decatur (maximum depth 18 feet) in Macon County, are examples of lakes that do not thermally stratify during summer.

During thermal stratification the upper water layer (the epilimnion) is isolated from the lower layer of water (the hypolimnion) by a temperature gradient (the thermocline). Temperatures in the epilimnion and hypolimnion, though different, are essentially uniform. When thermal stratification is established, the lake enters the summer stagnation period, so named because the hypolimnion becomes stagnant.

With cooler air temperatures in the fall the upper water layers commence to, cool. The temperature decrease continues until a uniform temperature is reached throughout the water column. The lake waters then begin the fall circulation period called 'fall turnover.'

Isothermal plots for Lake Eureka at an average summer water depth of 16 feet are shown in figure 10. The isotherms were developed from water temperature observations at approximately 7-day intervals. A thermal gradient began to develop in May at a water temperature of 10 to 12° C. The water temperature of the upper layers increased to 26° C within the 21-day period from May 10 to June 1. The temperature of bottom layers remained rather constant during this period at 10 to 12° C.

Lake Eureka surface waters reached a maximum temperature of 30° C on July 17. Bottom waters did not maintain a constant temperature typical of a firmly stratified lake. They varied from 10° C in April to 18° C in September. The maximum temperature differential occurred on July 17 when the temperature at the water surface was 30° C and that at the bottom was 13° C.

Figure 11 depicts typical temperature profiles at approximately 30-day intervals for Lake Eureka. Except for the profile for June 14 the thermocline was not distinctive, nor did the lower layers of the lake reflect a uniform temperature. Though the waters were thermally stratified at about 4 to 6 feet from the bottom, the regime was weak thus permitting some mixing of the warmer upper water layer with the lower water layer. Temperature increases in the lower bottom layers during the 5 months of 'summer stagnation' are evidence of casual mixing during the period.

The isothermal plots for Lake Canton are shown in figure 12 for an average water depth of 31 feet. The plots were prepared for the same time intervals mentioned for Lake Eureka. Thermal gradients began to develop in mid-May at a surface water temperature of 12° C. The temperature of the upper layers increased to 24° C within a 3-week period but the temperature of the bottom waters remained fairly constant at 10 to 12° C.

Surface waters reached a maximum temperature of 29° C on July 21. Unlike Lake Eureka, the temperature range of the bottom waters was narrow, varying from 10 to 12° C during the 5-month period of thermal stratification. This temperature range for bottom waters during stratification appears typical of most lakes 30 feet deep or greater in central and northern Illinois as reported by the Illinois State Water Survey (1978), Wang (1975), Kothandaraman and Evans (1975), and Kothandaraman et al. (1977) for Rend Lake, Lake Evergreen, Lake Bloomington, and Fox Chain of Lakes, respectively. Roseboom et al. (1978) observed bottom water temperatures of 14 to 16° C during thermal stratification in Cedar Lake located in southern Illinois.

The maximum temperature differential occurred on July 21 with water temperatures of 29° C at the surface and 11° C at the bottom.

Figure 13 depicts typical temperature profiles for Lake Canton. Unlike Lake Eureka, the thermal separation between the upper and lower layers is quite distinct. Well-defined thermal stratification occurred about 12 to 14 feet from the bottom. Since the water temperature of the bottom waters remained fairly uniform, mixing with the upper warm water strata was minimized which demonstrates the effectiveness of the stratification barrier.

In summary:

- The waters of Lake Eureka and Lake Canton thermally stratify during a 5-month period extending from mid-May to mid-October.
- The effectiveness of thermal stratification in Lake Eureka is less than that of Lake Canton as measured by the degree of temperature constancy in the lower water layers.

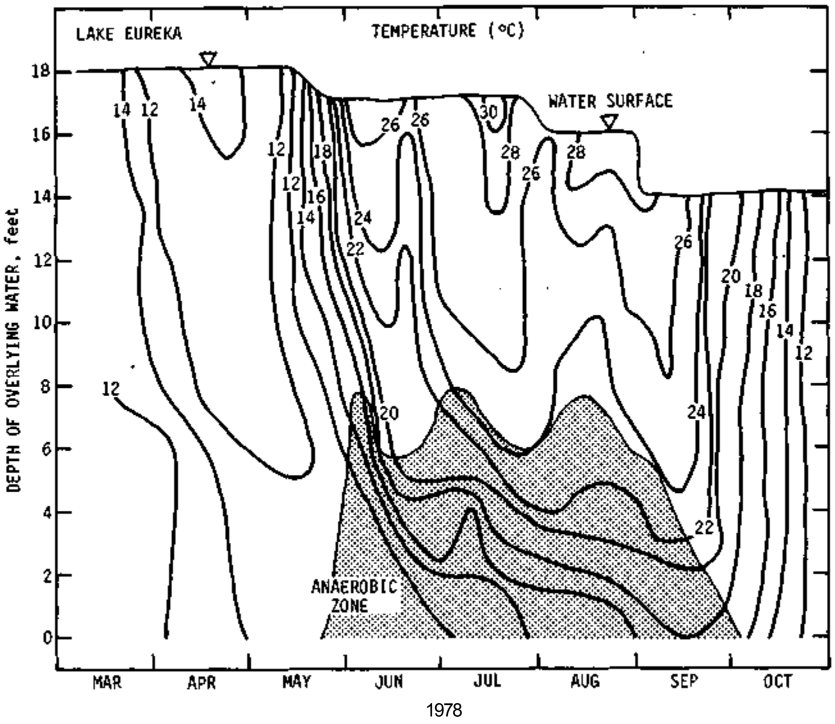


Figure 10. Isothermal plots. Lake Eureka

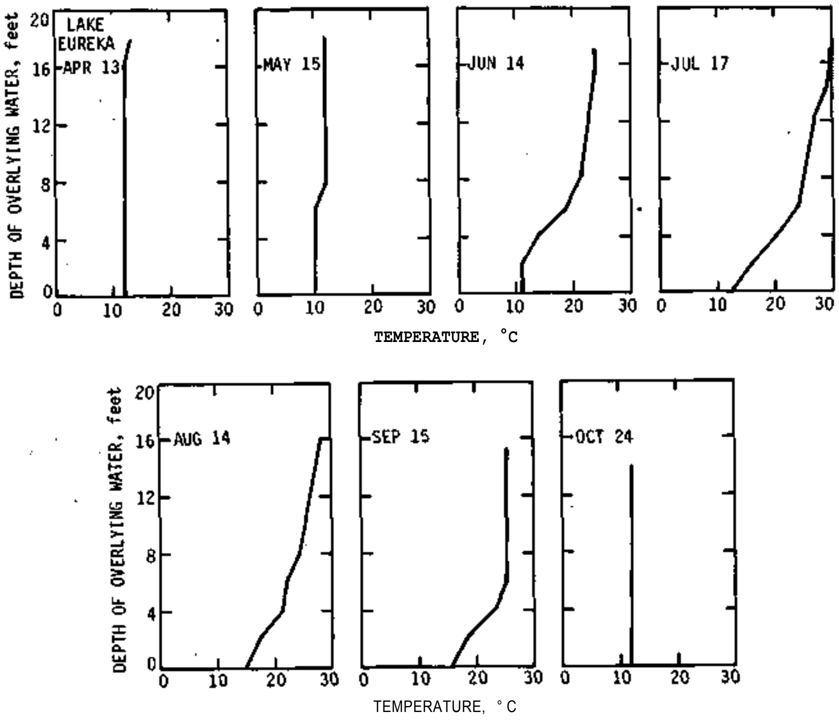


Figure 11. Temperature profiles. Lake Eureka

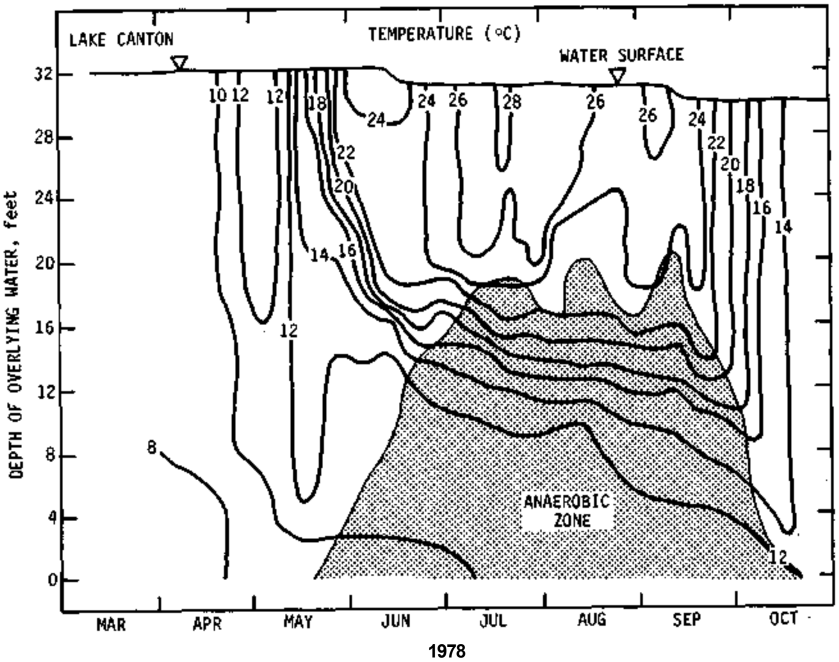


Figure 12. Isothermal plots. Lake Canton

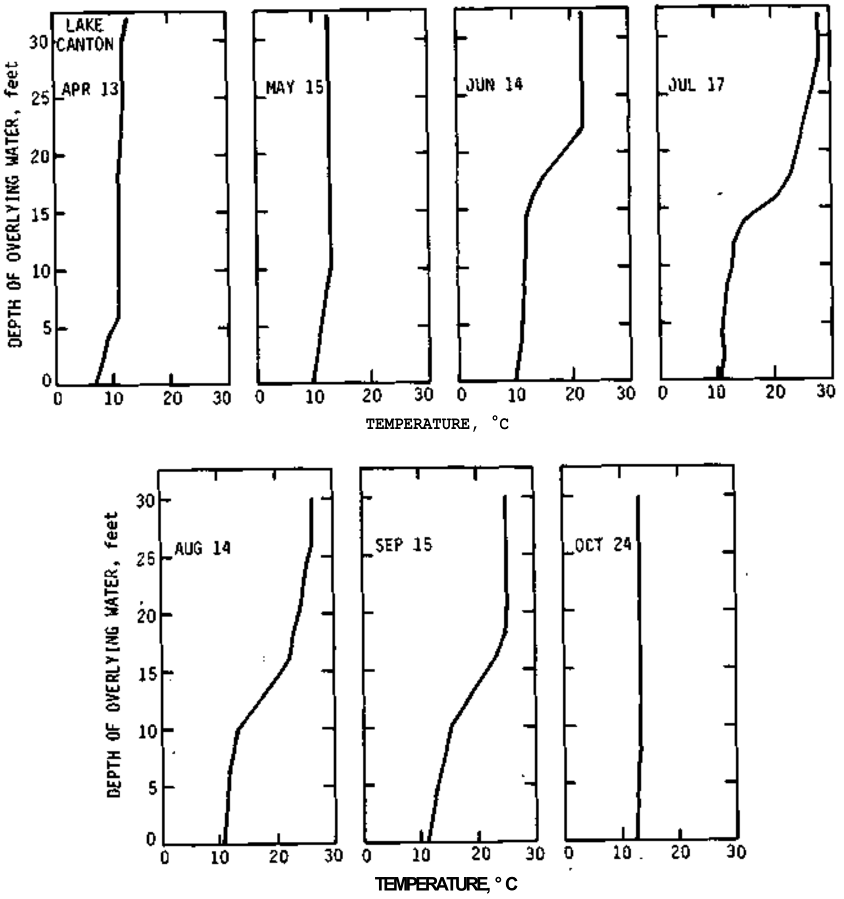


Figure 13. Temperature profiles. Lake Canton

- The less defined temperature stratification barrier for the shallower Lake Eureka occurs about 4 to 6 feet from the lake bottom. That for Lake Canton occurs about 12 to 14 feet from the bottom.
- Maximum surface water temperatures of 30 and 29° C, respectively, for Lake Eureka and Lake Canton were recorded during mid-July.
- During the period of thermal stratification the bottom water temperature at Lake Eureka varied from 10 to 18° C; that for Lake Canton varied from 10 to 12° C.

Dissolved Oxygen

For water quality in lakes the most important period is that of summer stagnation. The hypolimnion, by virtue of its stagnation, is a trap not only for decaying plant and animal matter that settle into it from overlying waters but also for those solubilized minerals, gases, and other products produced in the bottom muds. In Illinois lakes the lower layers of water become devoid of oxygen soon after their creation. In the absence of dissolved oxygen, the conditions become favorable for the release of nutrients, metals, gases, and other by-products from the bottom muds.

A major interest of this study was to observe the rate and extent of the formation of the anaerobic zones in Lakes Eureka and Canton. For this purpose dissolved oxygen measurements were performed at 1-foot intervals along the depth profile at Lake Eureka on 73 dates and at Lake Canton on 83 dates during a 6-month period.

Dissolved oxygen isopleths for Lake Eureka are shown in figure 14. On May 10 the water column contained about 7 to 8 mg/1 of dissolved oxygen. Thereafter a reduction in dissolved oxygen concentration in the bottom waters began. On June 5 the dissolved oxygen was depleted in the water column to a height of 8 feet from the bottom. For 3 months (June 1 to August 30) the layers of water extending from 6 to 8 feet from the lake bottom were devoid of dissolved oxygen. Water layers closer to the bottom were devoid of dissolved oxygen until September 30. The average water depth during the period of dissolved oxygen depletion was 16 feet. The extent and duration of the anaerobic zone is depicted as the 'shaded' portions of figures 14 and 10.

Dissolved oxygen profiles at approximately monthly intervals for Lake Eureka are shown in figure 15, which illustrates the progression of dissolved oxygen stratification. During the time of anoxic conditions in the lower waters the dissolved oxygen concentration in the surface waters varied from 6 to 16 mg/1.

The pattern of dissolved oxygen depletion in the lower water strata of Lake Canton was quite similar to that observed at Lake Eureka, but more extensive. As shown in figure 16 the bottom waters began to experience a reduction in dissolved oxygen on April 30 when the dissolved oxygen concentration in the water column was about 7 mg/1. On May 15 the bottom waters were devoid of dissolved oxygen and by July 15 the dissolved oxygen in the water column was depleted to a height of 19 feet from the bottom. Thereafter until September 30 (2½ months later) the lake waters extending from 14 to 20 feet from the bottom were devoid of dissolved oxygen. The lower layers were oxygen-depleted until October 15. The average water depth during dissolved oxygen stratification was 31 feet. The extent and duration of the anaerobic zone in Lake Canton is depicted in the shaded portions of figures 16 and 12.

Dissolved oxygen profiles for Lake Canton are shown in figure 17. As in Lake Eureka, surface waters occasionally achieved dissolved oxygen concentrations of 14 to 16 mg/1. These high concentrations occurred during mid-August and mid-September (figure 16), which is about the same time that the oxygen-depleted water reached its greatest height of 20 feet from the bottom.

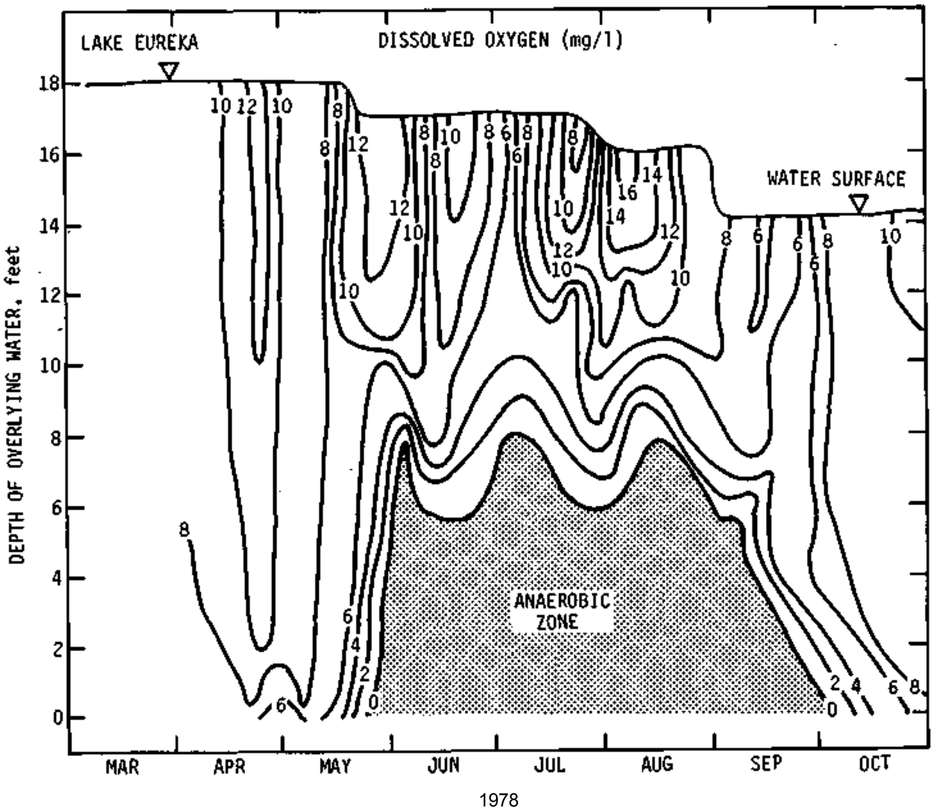


Figure 14. Dissolved oxygen isopleths. Lake Eureka

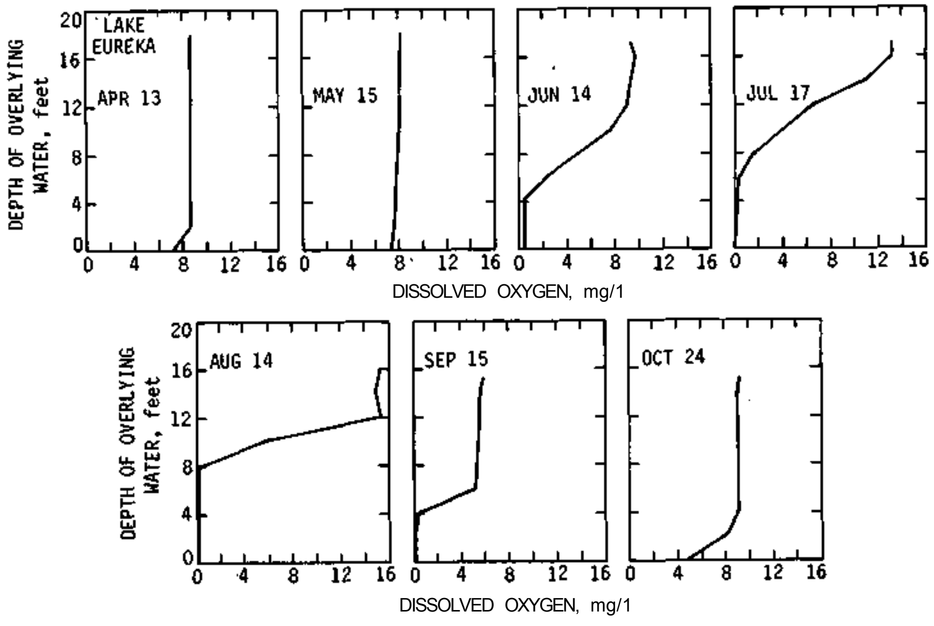
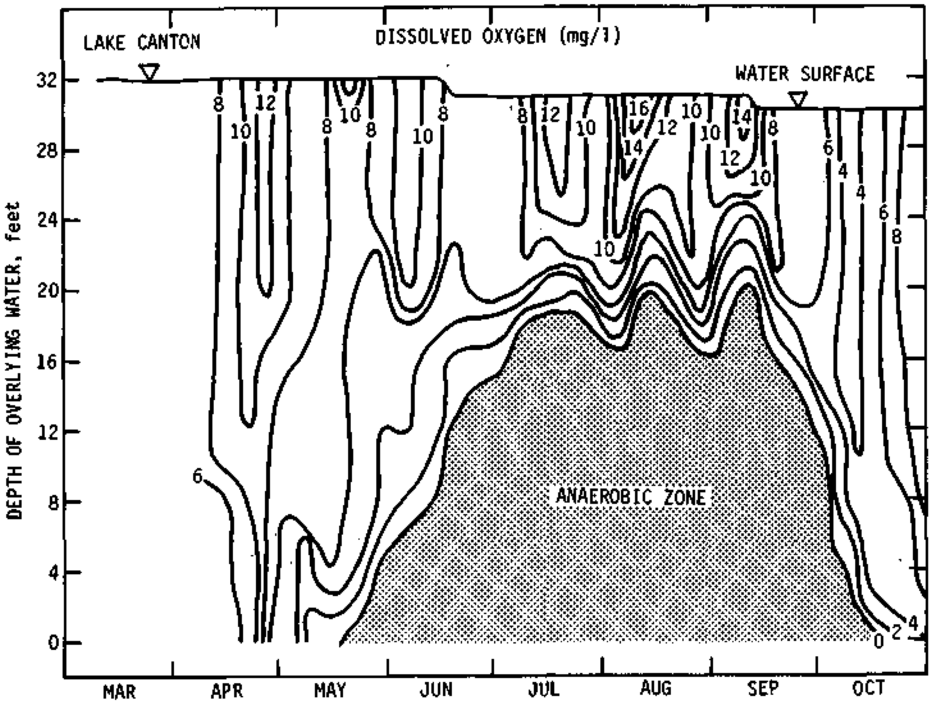
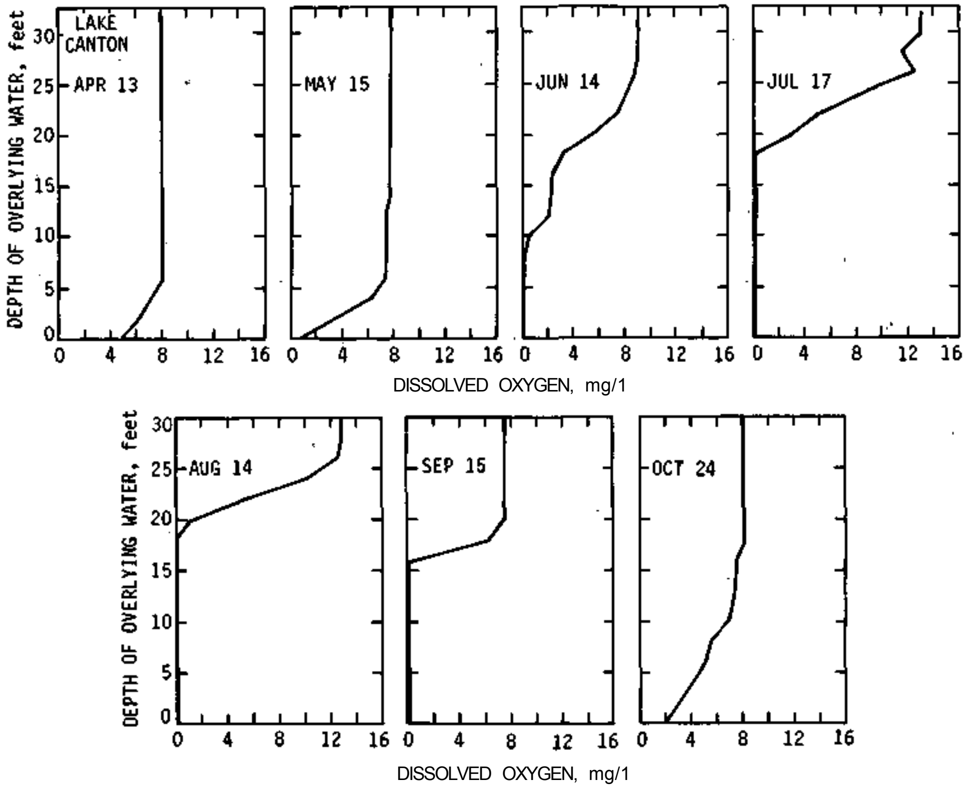


Figure 15. Dissolved oxygen profiles. Lake Eureka



1978

Figure 16. Dissolved oxygen isopleths. Lake Canton



DISSOLVED OXYGEN, mg/1

Figure 17. Dissolved oxygen profiles. Lake Canton

The anaerobic zone in Lake Eureka persisted for 4 months (June 1 to September 30) and during 75. percent of that time extended from 6 to 8 feet from the lake bottom. The anaerobic zone for Lake Canton lasted 5 months (May 15 to October 20) and during 50 percent of that time extended from 14 to 20 feet from the lake bottom.

The depiction of the anaerobic zone on the isothermal plots (figures 10 and 12) for both lakes provides for an interesting conclusion. As previously discussed, a rather weak thermal regime exists in Lake Eureka with a thermal stratification barrier occurring about 4 to 6 feet from the bottom. At Lake Canton, however, thermal stratification is well defined with a stratification barrier prevailing about 12 to 14 feet from the bottom. Since the anaerobic zone in Lake Eureka extends for some time 6 to 8 feet from the bottom and that zone for Lake Canton similarly extends 14 to 20 feet from its bottom, the 'barrier' to the mixing of the lake established by thermal stratification is no barrier to the vertical encroachment of the anaerobic zone.

Of major interest in this study was the *rate* at which dissolved oxygen becomes depleted in the hypolimnion. If the rate varies for different lake systems in a distinguishable fashion and if procedures can be devised to measure them indirectly, then rates of dissolved oxygen changes can be of practical importance in classifying lakes.

Two rates of oxygen reduction are involved. One is the rate of dissolved oxygen reduction within the lower strata of the water column as the anaerobic zone is formed. The other rate is that of dissolved oxygen depletion within the water column, i.e., the vertical rate of rise of oxygen-depleted water from the lake bottom. This rate is characterized by the slope of the lines depicting the dissolved oxygen isopleths during formation of the anaerobic zone.

Figure 18 is a simplified scheme depicting dissolved oxygen isopleths and the rationale used for determining the two rates. In developing rates for Lakes Eureka and Canton, reliance was placed on all data obtained during observations rather than just that data recorded at 7-day intervals used to prepare the isopleths plots in figures 14 and 16.

As mentioned earlier, the dissolved oxygen concentrations in the water column just prior to the formation of the anaerobic zone in Lake Eureka was 7 to 8 mg/1. As the zone began to develop the rates of dissolved oxygen reduction at three different strata were as follows:

Distance from bottom (feet)	*Rate of oxygen reduction (mg/l per day)*	*Coefficient of correlation (r)*
2	0.50	0.97
4	0.40	0.95
6	0.40	0.94

The rate of oxygen reduction in the bottom layers varied from 0.40 to 0.50 mg/1 per day. This rate cannot be considered the ultimate oxygen demand rate imposed upon the water layers because it is likely that mixing occurs between the three strata and the oxygenated overlying waters. The oxygen reduction rates determined for the three layers of bottom water represent the *net* rate of oxygen demand, i.e., the rate of oxygen demand in excess of the rate of oxygen replenishment.

The rates of rise in the water column (from the bottom) of oxygen-depleted water and of other dissolved oxygen concentrations are shown in the following tabulation:

Dissolved oxygen concentration (mg/l)	*Rate of rise (ft/day)*	*Coefficient of correlation (r)*
0	0.68	0.97
1	0.63	0.96
2	0.64	0.97
3	0.73	0.95
4	0.60	0.87

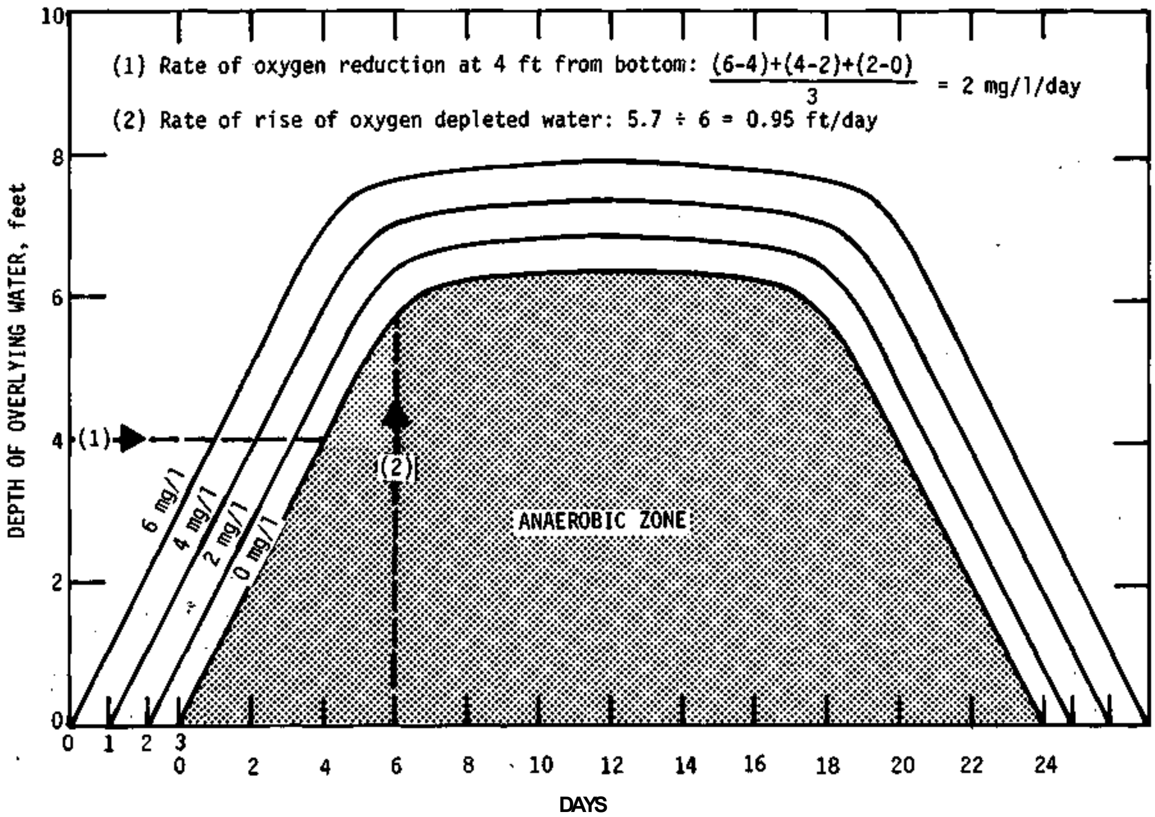


Figure 18. Simplified diagram depicting basic features of rate computations

The rate of rise of oxygen-depleted water in the water column was uniform at about 0.7 foot per day during the formation of the anaerobic zone, and rates for concentrations of 0 to 4 mg/1 ranged from 0.6 to 0.7 foot per day. On August 15 the vertical extent of the anaerobic zone from the lake bottom started to decline at a rate of about 0.15 foot per day. The anaerobic zone became extinct about September 30.

The rates for Lake Canton were similarly computed. Beginning with about 7 to 8 mg/1 of dissolved oxygen in the water column the rates of oxygen reduction in four water strata during the formation of the anaerobic zone are as follows:

Distance from bottom (feet)	*Rate of oxygen reduction (mg/l per day)*	*Coefficient of correlation (r)*
4	0.34	0.94
8	0.23	0.98
12	0.24	0.96
16	0.22	0.97

The rate of oxygen reduction in the lower layers varied with depth ranging from 0.22 mg/1 per day at 16 feet above the bottom to 0.34 mg/1 per day at the water stratum about 4 feet above the bottom. For comparable heights from the bottom the rate of reduction in Lake Eureka was higher than in Lake Canton.

Table 3. Oxygen Changes and Anaerobic Zone Migration

	Rate of oxygen reduction in lower strata (mg/l per day)	*Rate of rise of oxygen-depleted water (feet/day)*	*Rate of decline of oxygen-depleted water (feet/day)*
Lake Eureka	0.40-0.50	0.68	0.15
Lake Canton	0.22-0.34	0.36	0.50

The rates of rise of oxygen-depleted water from the bottom and of other dissolved oxygen concentrations are as follows:

Dissolved oxygen concentration (mg/l)	*Rate of rise (ft/day)*	*Coefficient of correlation (r)*
0	0.36	0.93
1	0.41	0.96
2	0.40	0.97
3	0.37	0.93
4	0.38	0.89

The rate of rise for dissolved oxygen concentrations ranging from 0 to 4 mg/1 was about 0.4 foot per day, which was less than the 0.6 to 0.7 foot per day observed at Lake Eureka. About September 10 the extent of the anaerobic zone from the bottom started to decline at a rate of 0.5 foot per day. The zone no longer existed on October 20. The rate of decline for the anaerobic zone in Lake Canton, at 0.5 foot per day, was about three times the rate of decline observed at Lake Eureka. A summary of the computed rates for the two lakes is given in table 3.

At an average water depth of 16 feet the volume of water in Lake Eureka is about 175 acre-feet. The volume of water devoid of oxygen during summer stagnation is 25 acre-feet or about 14 percent of the total lake volume. If it is accepted that waters containing less than 4 mg/1 of dissolved oxygen cannot support a desirable fishery, then about 25 percent of the lake volume of Lake Eureka is an unfit habitat for fish during summer months.

At Lake Canton, the water volume is about 3000 acre-feet at a 31-foot depth. The volume of water estimated to be void of dissolved oxygen on the average during summer months is 875 acre-feet or about 30 percent of the total lake volume. The volume of water with less than 4 mg/1 of dissolved oxygen during summer months is about 42 percent of the total lake volume.

In summary:

- The lower water strata of Lakes Eureka and Canton are void of dissolved oxygen during summer months.
- During the period of stagnation (June 1 through September 30) the anaerobic zone in Lake Eureka extends into the overlying water 6 to 8 feet from the bottom about 75 percent of the time. In Lake Canton the anaerobic zone extends 14 to 20 feet from the bottom about 50 percent of the time during the period May 15 to October 20.
- The thermal stratification of the lakes was not a barrier to the extent the anaerobic zone penetrates the overlying waters.
- As the anaerobic zone developed in the lakes the rates of oxygen reduction in the lower strata varied from 0.4 to 0.5 mg/1 per day for Lake Eureka and 0.22 to 0.34 mg/1 per day for Lake Canton.
- In Lake Eureka the rise of oxygen-depleted water in the water column was at a rate of 0.7 foot per day to an initial height of about 8 feet from the bottom. The rate of decline for oxygen-depleted water was 0.15 foot per day.

- In Lake Canton the rise of oxygen-depleted water in the water column was at a rate of about 0.4 foot per day to an initial height of 19 feet from the bottom. The rate of decline for the oxygen-depleted water was 0.5 foot per day.
- During summer months the volume of water in Lake Eureka and Canton containing less than 4 mg/1 of dissolved oxygen is 25 and 42 percent, respectively, of the total water volume.
- The volume of water completely void of oxygen during summer months is 14 and 30 percent, respectively, of the total volume of water in Lakes Eureka and Canton.

Alkalinity

The alkalinity of natural water is made up of three carbonic species. They are:

carbonic acid (H_2CO_3)
bicarbonate (HCO_3^-)
carbonate ($CO_3^=$)

The carbonic acid component is sometimes considered the carbon dioxide (CO_2) species. At a pH below 8.3 significant quantities of CO_2 do not exist in streams and lakes because of the following reaction:

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \qquad (1)$$

The three carbonic species are in equilibrium in stream and lake waters and the relative concentration of each is principally a function of the hydrogen ion (H^+) concentration, i.e., pH. Below a pH of 5 only H_2CO_3 is of quantitative importance. At a pH between 7 and 9 the HCO_3^- is of greatest significance and above pH 9.5 the $CO_3^=$ species predominates.

Most surface waters in Illinois have a pH range of 7 to 9 and the total alkalinity is predominantly in the form of bicarbonate. The dissociation of carbonic acid contributes to its formation as follows:

$$H_2CO_3 \rightleftarrows H^+ + HCO_3 \qquad (2)$$

When pH exceeds 9 the carbonate ion is formed thusly:

$$HCO_3^- \rightleftarrows H^+ + CO_3^= \qquad (3)$$

Under these conditions the $CO_3^=$ may precipitate and a loss of total alkalinity occurs.

Water samples for alkalinity measurements at Lakes Eureka and Canton were obtained with a Kemmerer sampler at 3 depths, i.e., at the water surface, near mid-depth or at that depth in the water column where zero DO conditions were initially recorded, and near the bottom of the lake (about 18 inches from the bottom). Samples were collected on 57 separate dates from each lake within the period April 23 to October 2 for Lake Eureka and from April 25 to October 16 for Lake Canton. All measurements were performed in the field.

In Lake Eureka at the water surface, concentrations ranged from 94 to 182 mg/1; those for the bottom water ranged from 150 to 301 mg/1. It is probable that the alkalinity of the waters, without chemical or biological influence, would range from 165 to 185 mg/1. This estimate is based on observations during early spring. In Lake Canton concentrations at the water surface ranged from 94 to 158 mg/1; that for the bottom water ranged from 137 to 273 mg/1. Without biological or chemical influence the alkalinity range of the lake's waters is 145 to 165 mg/1. This estimate too is based on early spring observations.

The extreme divergence in alkalinity concentration of the surface waters compared with bottom waters in the two lakes is shown in figures 19 and 20. Please note that the ordinate values of the figures increase in a descending order. As the temperature of upper strata of the lake waters increased, the alkalinity decreased. As anoxic conditions developed and were maintained in the deeper water strata, the alkalinity in those waters increased.

Increasing temperature in the upper layers of lake waters is conducive to increased biological activity, namely, algal growth. During the process of photosynthesis algae derive their source of carbon from HCO_3^- in mid western waters. The process may be expressed as:

$$[H^+ + HCO_3^-] \overset{\text{light}}{\rightarrow} CH_2O + O_2 \qquad (4)$$

Here the alkalinity, in the form of bicarbonate, is used to produce new celluar material (CH_2O) and dissolved oxygen (0_2). During the process the alkalinity in the water is reduced, and the dissolved oxygen and pH of the water increases.

In the absence of dissolved oxygen, a condition previously described for the lower water layers in the two lakes, there are several pathways for alkalinity concentrations to increase. The most influencial reaction is probably that of anaerobic metabolism whereby anaerobic bacteria convert the organic matter of bottom muds to $C0_2$ and methane (CH_4). A simplification of the process is as follows:

$$2CH_2O \overset{\text{bacteria}}{\rightarrow} CH_3COOH \overset{\text{bacteria}}{\rightarrow} CO_2 + CH_4 \qquad (5)$$

The $C0_2$ generated reacts with the water as described in equations 1 and 2. As a consequence the alkalinity in the form of HCO_3^- increases in the bottom waters and the pH decreases.

The concentrations of alkalinity in the waters at depths of 10 to 12 feet from the surface were not plotted but the monthly averages are shown in figures 19 and 20. It is clear that the values are more influenced by the upper water strata than by the lower water layers. This is not unexpected because the 10- to 12-foot water layer is still within the momentum of the circulation patterns established by the upper water layers. The October convergence of the alkalinity concentrations, shown in figures 19 and 20 for both water layers, is the result of fall turnover.

The decrease of alkalinity concentrations in the water at the surface and the increase of alkalinity in the bottom waters provide a relative measure of algal productivity in the upper water layers and of bacterial activity of the lower water layers of the two lake systems if certain assumptions are valid. Here it is assumed that the alkalinity changes in the upper strata of the lakes are governed by photosynthesis as stated in equation 4, and that the alkalinity changes in the lower strata of the lakes is governed by anaerobic fermentation as stated in equation 5.

Regression analyses were performed with alkalinity as the dependent variable and as a function of time. A summary of the analyses is given in table 4. Of particular interest is the rate of decrease and increase of alkalinity concentrations, respectively, in the surface and bottom waters of the lakes. At the water surfaces the rate of decrease for Lake Eureka was 0.79 mg/1 per day compared to a rate of decrease for Lake Canton of 0.60 mg/1 per day. The values suggest that algal productivity in Lake Eureka exceeds that in Lake Canton by 30 percent. At the bottom water layers the rate of alkalinity increase for Lake Eureka was 1.31 mg/1 per day compared to a rate of 0.85 mg/1 per day for Lake Canton. These values indicate that anaerobic activity in the bottom water strata of Lake Eureka exceeds that in Lake Canton by 54 percent.

In summary:

- Significant changes in alkalinity occur at the water surface and bottom layers of water in the two lakes. In Lake Eureka concentrations at the water surface ranged

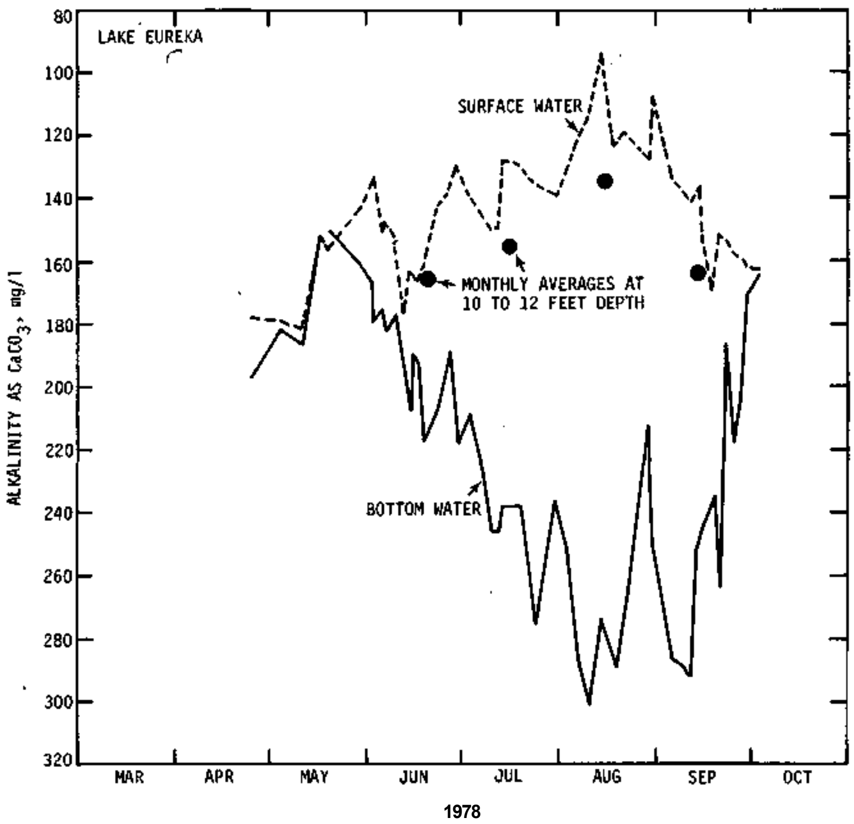


Figure 19. Total alkalinity. Lake Eureka

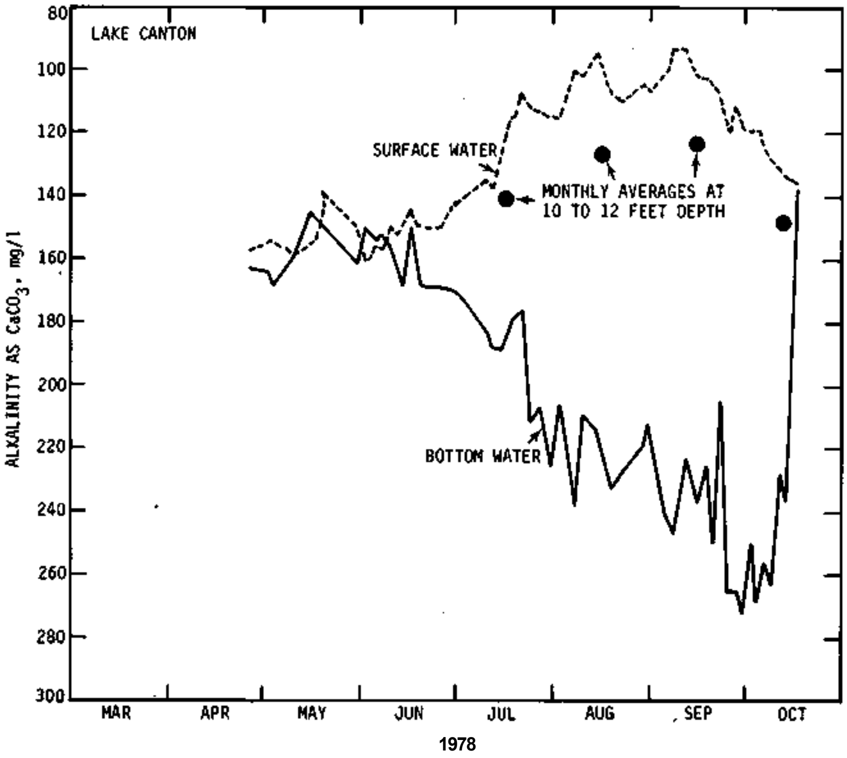


Figure 20. Total alkalinity. Lake Canton

Table 4. Regression Analyses of Alkalinity in Water Strata

	Period	*Equation*	
Lake Eureka			
Surface	**June 12 to August 14** **(64 days)**	**y = 163 – 0.79 x**	**0.85**
Bottom	**May 15 to August 14** **(91 days)**	**y = 154 + 1.31 x**	**0.87**
Lake Canton			
Surface	**June 14 to September 15** **(94 days)**	**y = 147 – 0.60 x**	**0.92**
Bottom	**June 9 to September 29** **(113 days)**	**y = 158 + 0.85 x**	**0.92**

Note: y = alkalinity in mg/l; x = number of days from beginning of period

from 94 to 182 mg/1; in Lake Canton they ranged from 94 to 158 mg/1. In the bottom waters of Lake Eureka the range was 150 to 301 mg/1; in Lake Canton they ranged from 137 to 273 mg/1.

- Alkalinity concentrations decreased at the water surface and increased in the lower water strata during periods of stagnation.
- The decrease of alkalinity at the water surface is the result of algal activity. The increase of alkalinity in the bottom waters is a function of anaerobic fermentation.
- Based on rates of alkalinity reductions the algal productivity in the surface waters of Lake Eureka exceeds that of Lake Canton by 30 percent. Similarly, the rates of alkalinity increases in the bottom waters of the lakes indicate that microbial activity in or near the bottom muds in Lake Eureka exceeds that in Lake Canton by 54 percent.

pH

pH is an expression of the hydrogen ion (H^+) concentration in water. It is commonly used to designate the intensity of acid and alkaline conditions in a water. The samples of water collected from Lakes Eureka and Canton for pH determinations were obtained in the same manner as described for alkalinity measurements.

The pH of the water surface of Illinois lakes increases during the summer months. The increase is influenced by algal growth. The mechanism causing the pH to increase has been described in equation 4. The pH at the water surface in Lake Eureka ranged from 8.0 to 9.2. In Lake Canton it ranged from 7.8 to 9.6.

In contrast, the pH of the bottom waters of Illinois lakes decreases during summer months, the depression becoming more acute during the period of stagnation. During this period acid-producing bacteria in the absence of oxygen break down organic material at the mud-water interface or within the bottom muds into fatty acids, alcohols, and other compounds. These intermediate products of fermentation are the energy sources for another group of bacteria which produce carbon dioxide, methane, ammonia, and hydrogen. These reactions have a profound influence on the pH of the water. The pH values of the bottom waters for Lake Eureka ranged from 8.3 to 7.2; those for Lake Canton ranged from 8.1 to 7.1.

The course of pH changes in the waters at the surface and near the bottom of the two lakes is shown in figure 21. Maximum pH values at the water surface occurred in August and September,

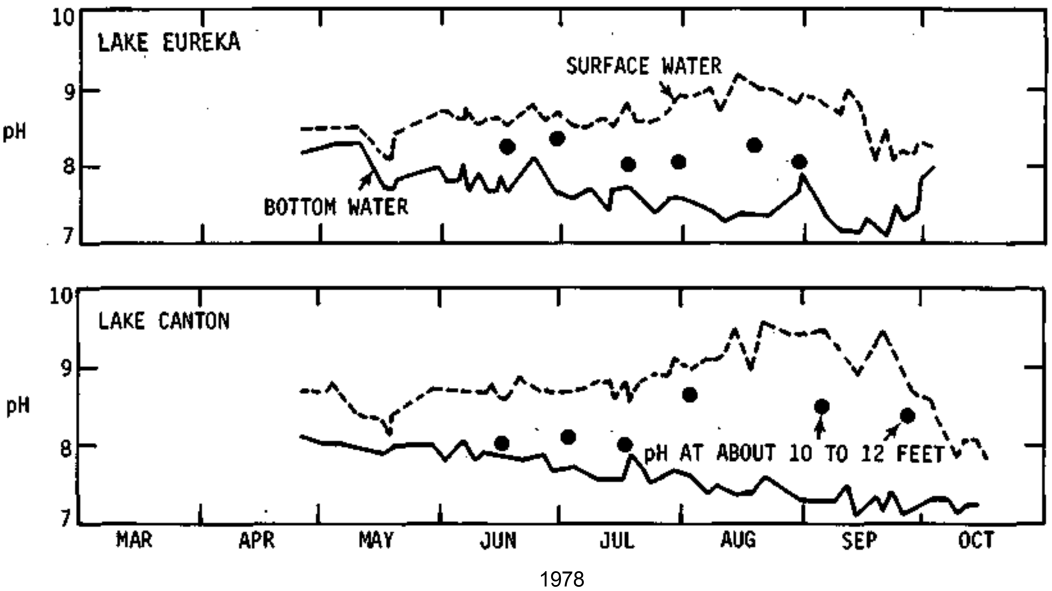


Figure 21. pH changes in the waters at the surface and near the bottom. Lakes Eureka and Canton

the period of maximum algal densities. The pH of the bottom waters reached minimum values during September. The changes in pH in the bottom waters are quite remarkable in light of corresponding increases of alkalinity in the waters. Alkalinity provides a resistance to pH change, i.e., buffering capacity. The forces responsible for significant decreases in pH in the face of well-buffered conditions have to be substantial.

Figure 21 also shows pH values for those water strata at 10 to 12 feet from the surface. The values generally lie about equidistant from the extremes suggesting that the top and bottom layers of water have about equal influence on them. Without the effects of chemical and biological reactions it is likely that the pH of the lakes' waters would be 8.0 to 8.2.

In summary:

- In Lake Eureka the pH at the water surface ranged from 8.0 to 9.2; in Lake Canton it ranged from 7.8 to 9.6.
- The pH in the bottom waters of the lakes was lower during the period of stagnation ranging from 8.3 to 7.2 at Lake Eureka and 8.1 to 7.1 at Lake Canton.
- Increasing pH values at the water surface were coincident with algal densities.
- Decreasing pH values in the bottom waters were consistent with the duration of the stagnation period.

Iron and Manganese

The determination of iron and manganese concentrations in the waters of the two lakes was not a planned activity of the study. As the investigation progressed it became apparent, since a major interest concerned the relationship of the lake bottom to the overlying water, that iron and manganese measurements would be worthwhile. Sullivan (1967) and Wang (1975) demonstrated that significant quantities of iron and manganese are released at the mud-water interface of lakes in Illinois during anoxic conditions. However, the extent of the migration of these metals into the overlying waters has not been documented for Illinois lakes.

Iron exists primarily in an aqueous environment in two oxidation states. In an oxidized state its form is ferric (Fe^{+++}); in a reduced state its form is ferrous (Fe^{++}). Generally Fe^{++} can exist only in extreme reducing conditions with dissolved oxygen concentrations less than 0.1 mg/1. In the presence of oxygen, Fe^{++} is oxidized to Fe^{+++}. The rate of reaction is rapid and theoretically 0.14 mg of oxygen is required for 1.0 mg of Fe^{++} oxidized. This suggests that iron in the form of Fe^{++} has a potential for reducing the dissolved oxygen concentration of water. Under some conditions, where the ratio of alkalinity to sulfide is minimal, Fe^{++} will be precipitated in the presence of sulfide.

Under anaerobic conditions one would expect Fe^{++} to predominate and under aerobic conditions Fe^{+++} is expected to dominate. However, in the presence of organic matter both Fe^{++} organic complexes and Fe^{+++} organic complexes can exist in natural water. Under these conditions Fe^{++} is resistant to oxidation under aerobic conditions and Fe^{+++} is resistant to reduction under anaerobic conditions.

The potential effects of iron in lake waters is not clear. However, Cowen et al. (1976) suggest that iron does exert a profound effect upon biological systems in a natural water. Iron, at levels of 0.1 to 1.0 mg/1, was reported by Morton and Lee (1974) to cause a shift in algal dominance from green to blue-green algae. And, in a study of six Wisconsin lakes, Bortleson and Lee (1974) concluded that iron is the primary factor for phosphorus levels in sediment. This leads to speculation that iron may govern the release rate of phosphorus from sediment. All of these observations coupled with the oxygen demand of iron in the Fe^{++} state indicate that the mechanisms for iron distribution in a lake system may play an important role in a lake's state of eutrophy.

The oxidation states of manganese are: Mn , Mn^{+++}, and Mn^{++++}. According to Morgan and Stumm (1965) the species Mn^{+++} does not occur in dissolved form in the absence of strong complexing agents. The solubility of Mn^{++++} is so low that it cannot be detected analytically. Thus the principal state of manganese occurring in natural waters is Mn^{++}. This was the finding of Delfino and Lee (1968) who report Mn^{++} was the main form of manganese measured in Lake Mendota throughout an entire seasonal cycle. Only Mn^{++} was detected in anoxic waters and Mn^{++} and Mn oxides were present in oxygenated waters. Unlike the oxidation of Fe^{++}, the rate of oxidation of Mn^{++} in the environment is slow. Morgan and Stumm (1965) suggest that the oxidation of Fe^{++} is accomplished at pH 7.2 and Mn^{++} requires a pH greater than 9.0 for any significant oxidation. Under laboratory conditions it took about 28 days to precipitate 0.60 mg/1 of manganese at a pH of 8.6 (Delfino and Lee, 1968). The point is that Mn^{++} does not appear to be a source of significant oxygen demand at low concentrations. This may not be the case for concentrations of manganese observed in the waters of Lakes Eureka and Canton.

Samples for iron and manganese analyses were obtained weekly from the two lakes during the period June to October. A Juday sampler was used and water was collected at varying depths but mainly in the anaerobic zones and at the mud-water interface. Analyses were performed for soluble ferrous iron, total soluble iron, and total soluble manganese. In most cases the total soluble iron consisted solely of soluble ferrous iron. In some instances the concentrations of the ferrous iron were reported to exceed the total iron. This impossibility is the result of the imperfections of the analytical procedures used. Nevertheless these results are included in the appendix section.

Iron and manganese are released from the sediments of Illinois lakes during anoxic conditions. Low concentrations are found throughout the lake waters during times of free circulation. As the metals are released from the sediment they tend to concentrate at the mud-water interface. These concentrations can be substantial. From the interface the metals migrate into the overlying waters.

The concentrations of iron and manganese observed at the interface of Lakes Eureka and Canton are shown in table 5. Iron was recorded as high as 31.4 mg/1 and 92.0 mg/1, respectively, for Lake Eureka and Lake Canton. Manganese reached peaks of 7.82 mg/1 and 16.04 mg/1, respectively, for the two lakes. It is obvious that powerful reducing conditions exist at the mud-water interface.

The extent of ferrous iron migration in the water column of the lakes is shown in figure 22. For Lake Eureka the concentration in the water strata 2 feet from the bottom exceeded 9.0 mg/1 during the month of August. The ferrous iron concentration increased at a rate of 0.4 mg/1 per day. The concentrations in the water layer 4 feet from the bottom reached a peak of 3.5 mg/1 but generally it averaged about 1.5 mg/1. In the layer of water 6 feet from the bottom ferrous iron concentrations were limited to about 0.5 mg/1. The penetration of significant ferrous iron was limited to 6 feet from the bottom which is about the average height of the anaerobic zone.

Although iron concentrations in the interface waters were generally higher in Lake Canton than in Lake Eureka the concentration in the layer of water 2 feet from the bottom in Lake Canton (figure 22) was substantially lower. Also the concentrations of iron in the different strata of water for that lake showed less difference between and less fluctuation within the strata than in Lake Eureka. This is probably a result of an unstable thermal regime in Lake Eureka which permitted more mixing in the lower reaches of the lake.

The estimated rate of ferrous iron increases in the different water layers at Lake Canton before levels became stable were 0.11, 0.08, 0.08, and 0.02 mg/1 per day at 2, 4, 6, and 10 feet from the lake bottom, respectively.

Table 5. Concentrations of Soluble Iron and Manganese at the Mud-Water Interface
(Concentrations in mg/1)

	Lake Eureka		*Lake Canton*	
Date	*Iron*	*Manganese*	*Iron*	*Manganese*
5/29	<0.17	0.73	1.00	3.03
6/5	<0.19	0.39	3.90	5.56
6/12				
6/19	2.19	3.41	33.30	7.41
6/26	2.10	2.47	5.52	4.04
7/3	14.48	3.96	36.80	12.22
7/10	17.90	5.62	18.20	6.60
7/17	4.13	4.45	29.20	9.37
7/24	7.54	5.08	63.00	8.98
7/31	8.85	5.17	59.50	11.67
8/7	12.10	5.66	7.50	7.76
8/14	11.70	5.29	22.95	6.57
8/21	16.10	5.29	2.33	3.96
8/28	9.90	4.16	19.00	5.44
9/5	12.40	5.58	3.78	5.12
9/11	14.70	5.69	21.76	6.75
9/18	26.50	7.19	2.81	5.09
9/25	31.40	7.82	92.00	16.04
10/2	2.63	0.51	78.30	14.62
10/9			50.20	9.40
10/16			50.20	7.50

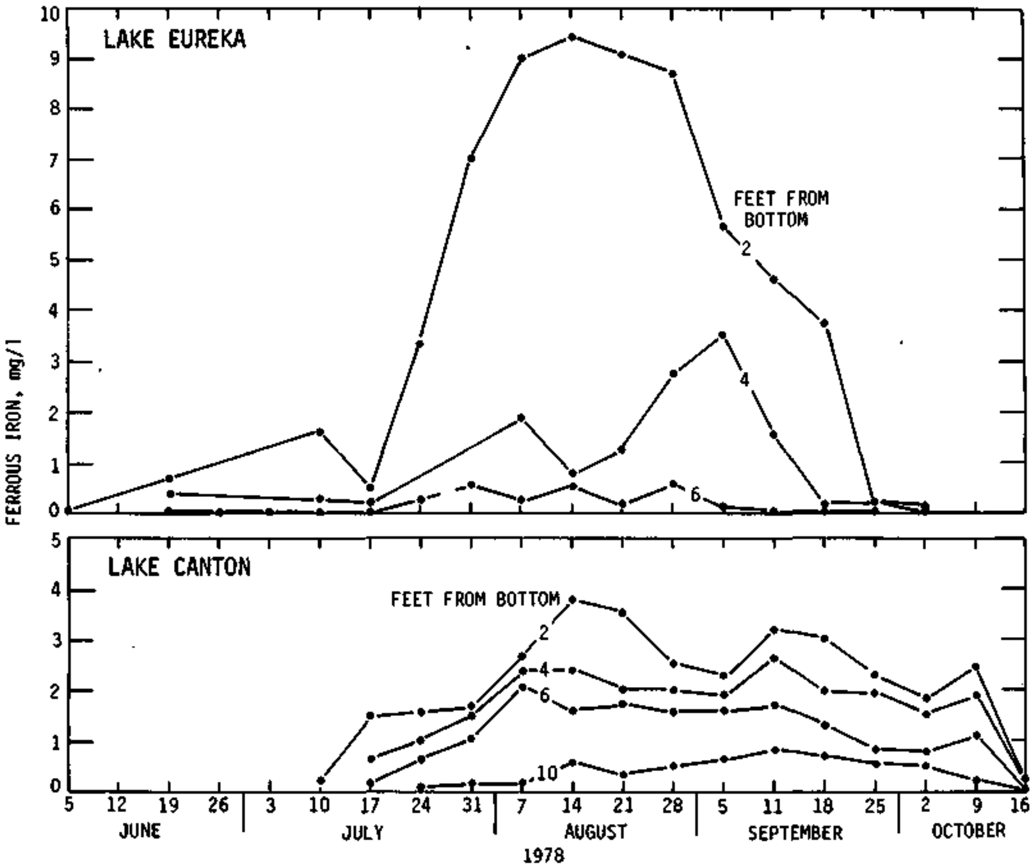


Figure 22. Soluble ferrous iron concentrations in the water column at different depths from the bottom. Lakes Eureka and Canton

The penetration of significant concentrations of ferrous iron in the water column at Lake Canton reached 10 feet from the bottom compared with the limit of 6 feet in Lake Eureka.

A similar examination of manganese migration for the two lakes is shown in figure 23. Concentration gradients were less in Lake Canton than in Lake Eureka, but the range of manganese concentrations, presumably Mn^{++}, of about 1.0 to 5.0 mg/l within the penetration zone was the same. However, the extent of Mn^{++} penetration within the water column differed. In Lake Eureka the zone of significant penetration was 6 feet from the bottom; in Lake Canton the limit was 16 feet from the bottom.

The configuration of the manganese data with time did not permit an estimate of the rate of manganese buildup in the water layers. It is probably less than that computed for ferrous iron based upon the reported rate of increase by Delfino and Lee (1971) of 0.015 mg/l per day in the bottom waters of Lake Mendota.

The limit of vertical migration of these metals in the lakes seems to be a function of the vertical extent of the anaerobic zone. The reasons for significant ferrous iron concentrations extending in the water column of Lake Canton to only 10 feet when significant Mn^{++} concentrations extended to 16 feet are speculative. This may be due to the Fe^{++} being readily oxidizable whereas Mn^{++} is not. If this is the case, than Fe^{++} may be an important oxygen demanding substance in the water column contributing to the vertical extent of the anaerobic zone. This reasoning is con-

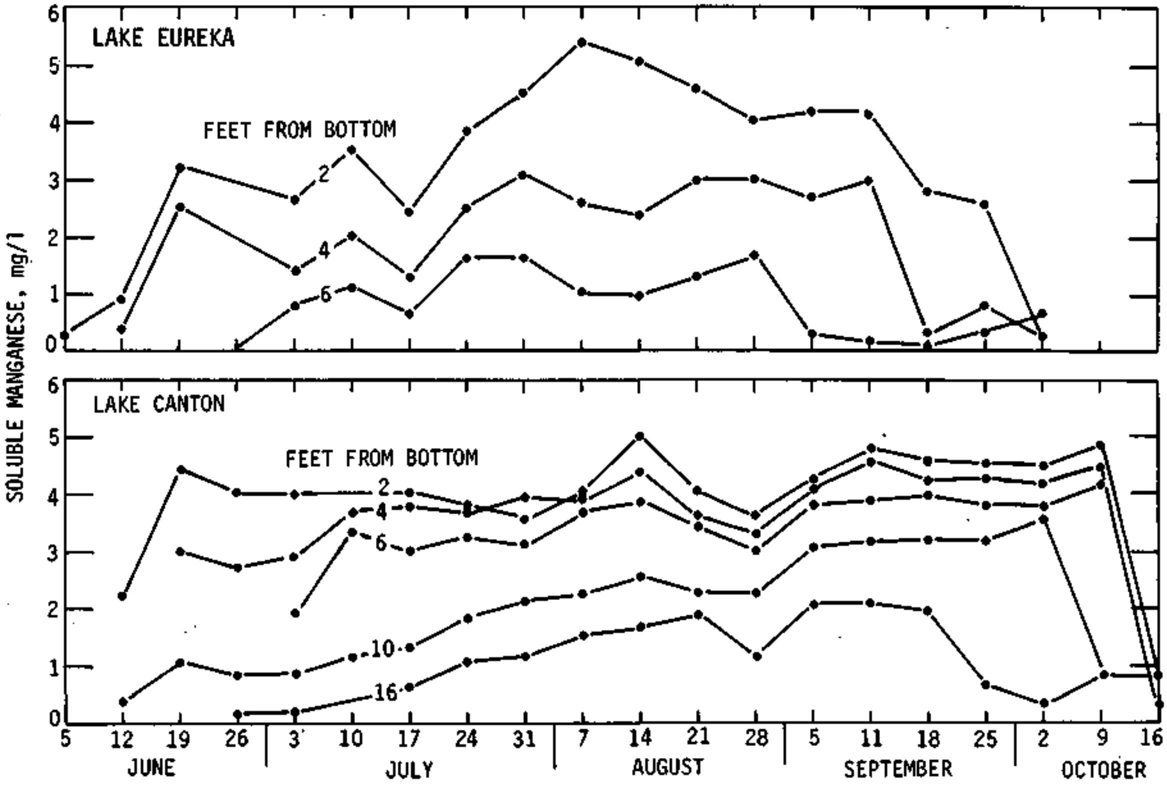


Figure 23. Soluble manganese concentrations in the water column at different depths from the bottom. Lakes Eureka and Canton

sistent with the relatively low concentrations of iron observed at the 6-foot level in Lake Eureka compared with those observed in its water layers 2 and 4 feet from the bottom.

In summary:

- Significant quantities of iron and manganese are released from lake bottoms during anoxic conditions.
- Iron is predominantly in the ferrous (Fe^{++}) state and readily oxidizable. Manganese is in the manganous (Mn^{++}) state, and not readily oxidizable. Consequently, iron is a source of oxygen demand in bottom waters.
- Iron and manganese migrate up the water columns of lakes. The limit of manganese migration appears to be the vertical extent of the anaerobic zone. Iron migration may be limited by oxidation conditions.
- In Lake Eureka iron concentrations in the 2-foot strata increased at a rate of 0.4 mg/l per day. The rate of iron increases in various bottom layers in Lake Canton varied from 0.02 to 0.11 mg/l per day.
- On the average the concentration of soluble iron and manganese at the interface was higher in Lake Canton than in Lake Eureka. However, the average concentration of ferrous iron in the bottom waters of Lake Eureka (4.85 mg/l) was higher than that observed at Lake Canton (2.27 mg/l).

Ammonia-Nitrogen

Nitrogen in the aquatic environment occurs in several important forms. Those forms of primary interest in lake waters include organic nitrogen, inorganic nitrate, and ammonia. Organic nitrogen is usually more prevalent in the protoplasm of aquatic plants, either free-floating or rooted, and is derived principally from ammonia and nitrate uptakes. Nitrate-nitrogen concentrations in most Illinois impoundments are less than 4 mg/1; however, several lakes in central and east-central Illinois on streams coursing highly productive agricultural lands have concentrations exceeding 10 mg/1. These are special cases. Ammonia-nitrogen, except in the deeper water layers of Illinois impoundments, rarely exceeds 0.5 mg/1 except during periods of turnover.

Nitrogen can stimulate algal growth, depress dissolved oxygen through the process of nitrification, become toxic to aquatic life, create public health problems, and interfere with the efficiency of chlorination disinfection. Ammonia-nitrogen is involved in all these processes. Because of emphasis on the effect of lake bottoms on the water quality of the overlying water, nitrogen determinations during the course of this study were limited to ammonia-nitrogen.

Samples were collected for analyses at the same time and in the same manner as described for iron. Samples were taken at the water surface, but the majority of the collections were within the anaerobic zone in both lakes.

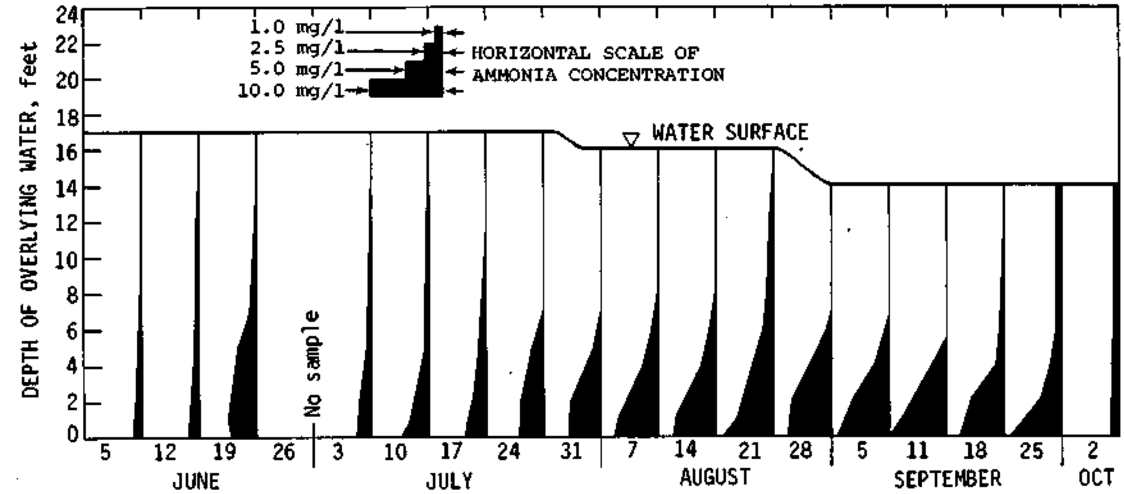
The range of concentrations encountered and the penetration of the concentrations into the overlying water from the lake bottom are shown in figures 24 and 25, respectively, for Lake Eureka and Lake Canton. Ammonia-nitrogen production from the bottom muds, under anaerobic conditions, is substantial.

The accumulation in the bottom waters started in Lake Eureka in June. As time progressed (see figure 24) concentrations in excess of 5 mg/1 occurred during August and September in the bottom 2 feet of water. Significant concentrations generally did not penetrate the 6- to 8-foot layer until the lake turnover in late September and early October. On the other hand, ammonia-nitrogen in Lake Canton (figure 25) did not reach concentrations in excess of 5 mg/1 in the 2-foot layer until September but persisted through early October until dispersal at the time of turnover. However, significant concentrations penetrated to the height of 16 to 20 feet from the bottom. The penetration, as in the case of Lake Eureka, is consistent with the vertical extent of the anaerobic zone of each lake.

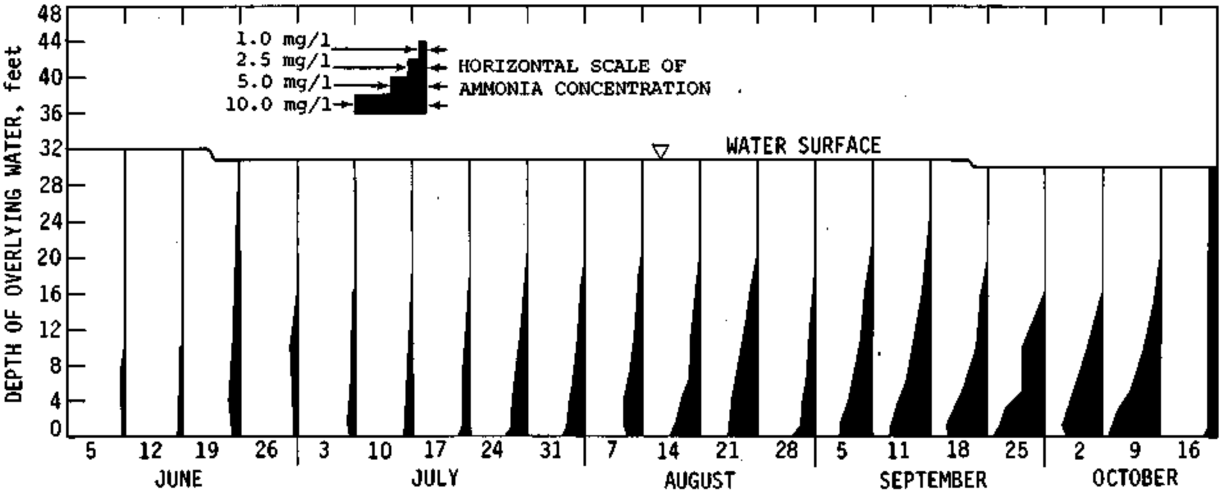
The production of ammonia-nitrogen in lake bottoms in Illinois is not unusual. A comparison of Lakes Eureka and Canton with other Illinois lakes is shown in table 6. With the exception of Cedar Lake (Lake County) which is mainly spring-fed, and Rend Lake which does not sustain an anaerobic zone, the concentrations observed are comparable.

Table 6. Comparison of Ammonia-Nitrogen in Bottom Waters of Illinois Lakes

Lake	*Depth (feet)*	*Mean (mg/l)*	*Range (mg/l)*
Eureka	**17**	**3.97**	**0.43-7.11**
Canton	**31**	**3.04**	**0.64-6.19**
Catherine	**39**	**2.12**	**0.20-7.50**
Marie	**31**	**1.22**	**0.06-3.85**
Channel	**35**	**2.17**	**0.07-8.48**
Bluff	**27**	**2.76**	**0.05-9.15**
Cedar (Lake Co.)	**42**	**0.96**	**0.01-1.94**
Rend	**31**	**0.13**	**0-0.28**



1978
Figure 24. Ammonia-nitrogen concentrations. Lake Eureka



1978
Figure 25. Ammonia-nitrogen concentrations. Lake Canton

Because the extent of significant ammonia-nitrogen concentrations in Lakes Eureka and Canton is generally within the vertical limits of the anaerobic zone, it is conceivable that the rate of ammonia production is a major influence on the maintenance of the vertical height of the zone. In the presence of oxygen and nitrifying bacteria, ammonia-nitrogen can be converted to nitrate. The process of nitrifying 1 mg/l of ammonia-nitrogen requires 4.57 mg/l of dissolved oxygen. If nitrification indeed occurs within the lake system, there obviously are sufficient quantities of ammonia produced to impose a significant demand on the oxygen resources of the overlying waters.

In summary:

- Significant quantities of ammonia-nitrogen are produced in the lakes during the period of stagnation.
- In Lake Eureka concentrations in excess of 5 mg/1 occurred in the bottom 2 feet of water during August and September. Concentrations in excess of 1 mg/1 rarely extended beyond the 6- to 8-foot layers.
- In Lake Canton concentrations in excess of 5 mg/1 occurred in the bottom 2 feet of water during September and October. Concentrations in excess of 1 mg/1 rarely extended beyond the 16- to 20-foot layers.
- The limit of significant ammonia-nitrogen concentrations was consistent with the vertical limit of the anaerobic zones.
- The levels of ammonia-nitrogen concentrations in the bottom waters of Lakes Eureka and Canton were similar to those of other Illinois lakes.
- Ammonia-nitrogen has the oxygen demand potential to influence the extent and duration of the anaerobic zone of Illinois lakes.

Phosphorus

Phosphorus availability is the critical nutrient governing biological activity in Illinois waters. The various fractions and forms of phosphorus in Illinois'waters have been reported by Sullivan and Hullinger (1969). In this study only total and dissolved phosphorus were examined. Total phosphorus includes particulate and dissolved phosphorus. Dissolved phosphorus is the form more readily available for biological uptake.

It is not unusual for mean total phosphorus levels in Illinois streams to exceed 0.1 mg/1 (Butts et al., 1976; Kothandaraman et al., 1977; Illinois State Water Survey, 1974, 1978). Where the watershed drainage to streams is predominantly rural, the dissolved phosphorus concentration varies from about 25 to 35 percent of the total phosphorus. However, where treated domestic waste effluents contribute significantly to streamflow, the dissolved phosphorus is likely to represent 60 to 80 percent of the total phosphorus.

The phosphorus levels in Illinois lakes, with the exception of those waters close to the lake bottom, are less than those in their tributary streams. Since most of the phosphorus entering the lakes is in the particulate form (65 to 75 percent) it is reasonable to expect a major portion of the nutrient to settle to the bottom. Sedimentation coupled with biological uptake and dilution are responsible for *lowering* total phosphorus levels in overlying lake waters but *increasing* levels in the bottoms. Within the lake system itself there is a cycling of phosphorus. From the bottom, during periods of stagnation, soluble phosphorus can be generated for uptake by algae. Those algal cells not flushed out of the system return phosphorus to the bottom by settling.

During examination of lakes of the Fox Chain (Kothandaraman et al., 1977) the dissolved phosphorus in waters at the surface made up 25 to 38 percent of the total phosphorus. In waters near the bottom, dissolved phosphorus ranged from 40 to 80 percent of the total phosphorus. This is comparable to the influence of treated sewage on stream waters in terms of dissolved and total phosphorus relationships.

Samples for phosphorus determinations were taken in the same manner and at the same time interval described for chlorine demand collections. Samples were analyzed for total and dissolved phosphorus at the water surface, at mid-depth, and near the bottom. The results are summarized in table 7.

Table 7. Concentrations of Total and Dissolved Phosphorus
(Concentrations in mg/l)

	Lake Eureka		*Lake Canton*	
	Mean	*Range*	*Mean*	*Range*
Total phosphorus				
Surface	**0.06**	**0.02-0.11**	**0.05**	**0.02-0.14**
Mid-depth	**0.06**	**0.03-0.14**	**0.05**	**0.02-0.14**
Near bottom	**0.12**	**0.06-0.28**	**0.32**	**0.06-0.78**
Dissolved phosphorus				
Surface	**0.02**	**0.00-0.06**	**0.02**	**trace-0.06**
Mid-depth	**0.02**	**trace-0.03**	**0.03**	**0.01-0.05**
Near bottom	**0.02**	**0.00-0.08**	**0.17**	**0.01-0.53**

As shown in table 7, differences in total phosphorus concentrations in surface waters and in mid-depth waters, either within the lakes or between them, are small. The average levels and range of values are quite similar. Mean values at the surface and at mid-depth are 0.05 to 0.06 mg/l with an overall range for both lakes of 0.02 to 0.14 mg/l. In the bottom waters, the mean concentration at Lake Eureka is 0.12 mg/l and the mean level at Lake Canton is almost three times that, 0.32 mg/l.

The dissolved phosphorus concentrations in the water column of Lake Eureka do not differ significantly (table 7). The dissolved phosphorus levels are the same from the top to the bottom averaging 0.02 mg/l. And, as in the case of total phosphorus, there is little difference between the surface water and mid-depth in Lake Canton and between the waters of the two lakes at these depths. The bottom waters of Lake Canton, however, are exceedingly productive in terms of dissolved phosphorus. The differences between dissolved phosphorus concentrations in the bottom waters of the two lakes are shown in figure 26.

The mean levels in Lake Canton are about nine times that found in Lake Eureka, i.e., 0.17 mg/l versus 0.02 mg/l. Therefore the major differences, where such exist between the two lakes, lies in the relative proportions of dissolved phosphorus to total phosphorus in their waters. On the average, that portion of total phosphorus in the form of dissolved phosphorus in Lake Eureka is about 28 percent and that in Lake Canton about 52 percent. This is a substantial difference. Since the dissolved form is more readily available as a nutrient for biological uptake, the potential of Lake Canton to support algal growth would exceed that of Lake Eureka if the total phosphorus levels were equal. However, the total phosphorus in the bottom waters in Lake Canton exceeds by about three times that in Lake Eureka. Therefore the capacity of Lake Canton waters to support organic biomass is considerably greater than that of Lake Eureka waters.

In summary:

- Phosphorus in dissolved form is more readily available for biological uptake than particulate phosphorus.
- In rural Illinois streams, dissolved phosphorus represents about 25to 35 percent of the total phosphorus. Except near the bottom, the proportion of dissolved phosphorus in most Illinois lakes is about the same as that observed in streams.
- Within lake systems phosphorus may be solubilized in the bottom muds, introduced into the overlying waters, taken up by aquatic plants, and returned to the bottom upon decay.

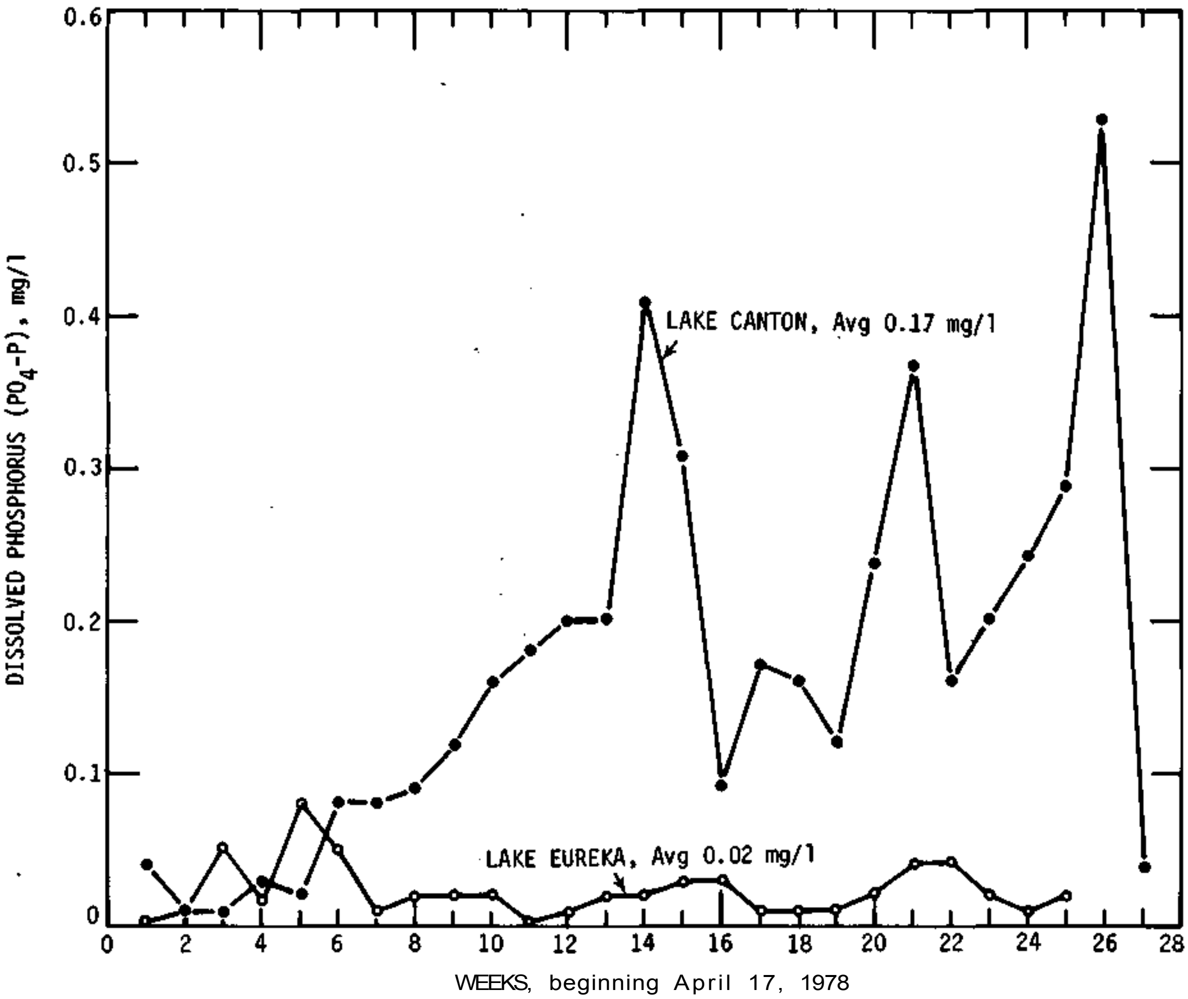


Figure 26. Concentrations of dissolved phosphorus in bottom waters

- There was very little difference in the phosphorus content of water at the surface and at mid-depth in Lakes Eureka and Canton. The average values for these depths were 0.05 to 0.06 mg/l for total phosphorus and 0.02 to 0.03 mg/l for dissolved phosphorus.
- The total phosphorus in bottom waters was about three times as high in Lake Canton as in Lake Eureka, i.e., 0.32 versus 0.12 mg/l. Dissolved phosphorus in the bottom waters of Lake Canton exceeded that in Lake Eureka about nine times, i.e., 0.17 versus 0.02 mg/l.
- On the average, the dissolved portion of total phosphorus in the waters of Lake Canton was about 52 percent compared with 28 percent for Lake Eureka.
- On the basis of phosphorus concentrations in the bottom waters and particularly the relative proportion of dissolved phosphorus, the capacity of Lake Canton to support organic biomass considerably exceeds that of Lake Eureka.

Chlorine Demand

Chlorine demand analysis is not usually applied to assess the quality of lake water. Its application is mainly limited to determining the required dosage of chlorine for potable water supplies and wastewater effluents. Because the chlorine demand of a water is dependent on the concentration of such inorganic reductants as ferrous iron, manganous manganese, and sulfide in water, it is an indirect measure of the oxidizing potential of these substances.

When chlorine is introduced into water either in gaseous form (Cl_2) or as a hypochlorite ($Ca(OCl)_2$) the same end products are produced. These are hypochlorous acid (HOC1) and the hypochlorite ion ($OC1^-$). Chlorine, hypochlorous acid, and hypochlorite ions in water are considered *free residual chlorine.* If ammonia is present, its reaction with chlorine and hypochlorous acid produces chloramines. Chloramines in water are referred to as *combined residual chlorine.* The *total chlorine residual* in water is the sum of the free and combined residual chlorine.

The chlorine demand of a water is the difference between the initial concentration of chlorine in the sample, after dosage with a stock chlorine solution, and the measured residual chlorine after a specified time of contact. For this study contact was limited to 30 minutes. The method used for analysis was the Iodometric Method I outlined in *Standard Methods* (American Public Health Association, 1975). This method measures the total chlorine residual. In retrospect it would have been informative if a method had been used that would have permitted determinations for free and combined residuals as well as total residuals.

Samples were collected from the two lakes at weekly intervals beginning April 17 at three depths, i.e., surface, mid-depth, and near the lake bottom. Sampling terminated at Lake Eureka on October 2 and at Lake Canton on October 16. Data are not available to compare the results obtained for these two lakes with other lake systems.

The results for chlorine demand at the water surface, at mid-depth, and near the bottom are shown in figures 27 and 28, respectively, for Lake Eureka and Lake Canton. Chlorine demand of the surface water averaged about the same for each lake, i.e., 4.2 to 4.3 mg/1. Without the high values that occurred during the last 2 to 3 weeks of sampling at the surface, presumably the effect of fall turnover, the average chlorine demand was 3.8 mg/1 for each lake. In the absence of data from other lakes the average chlorine demand of 3.8 mg/1 can be considered background for the two lake systems.

As shown in the figures there was no trend in the chlorine demand values for the surface or mid-depth waters. The average values for mid-depth conditions were higher in Lake Canton than in Lake Eureka, i.e., 5.1 versus 4.3 mg/1. Eliminating the two high values that occurred in Lake Canton at mid-depth during the last 2 weeks, the comparison of average values is 4.6 versus 4.3 mg/1. At mid-depth (about 16 feet from the bottom) in Lake Canton the sampling point is well within the upper limits of the anaerobic zone. At Lake Eureka the mid-depth is about 8 feet from the bottom which places the sampling point at the extreme limit of the anaerobic zone. This may account for the slightly higher values found at the mid-depth water strata of Lake Canton compared with mid-depth at Lake Eureka.

In the bottom waters the average chlorine demand for Lake Eureka was 9.2 mg/1 versus an average of 11.3 mg/1 at Lake Canton. Unlike the waters of the upper strata the bottom waters experienced a definable rate of increase during the 12-week period from April 17 to July 3. The rate of increase in chlorine demand for Lake Eureka was about 0.95 mg/1 per week versus about 0.75 mg/1 per week for Lake Canton. On the 12th week of sampling (July 3) all water strata displayed a similar peak. This followed a series of severe thunderstorms that occurred during the . weekend of July 1-2. After the 12th week, there was no distinguishable trend in chlorine demand values in either lake for the bottom strata.

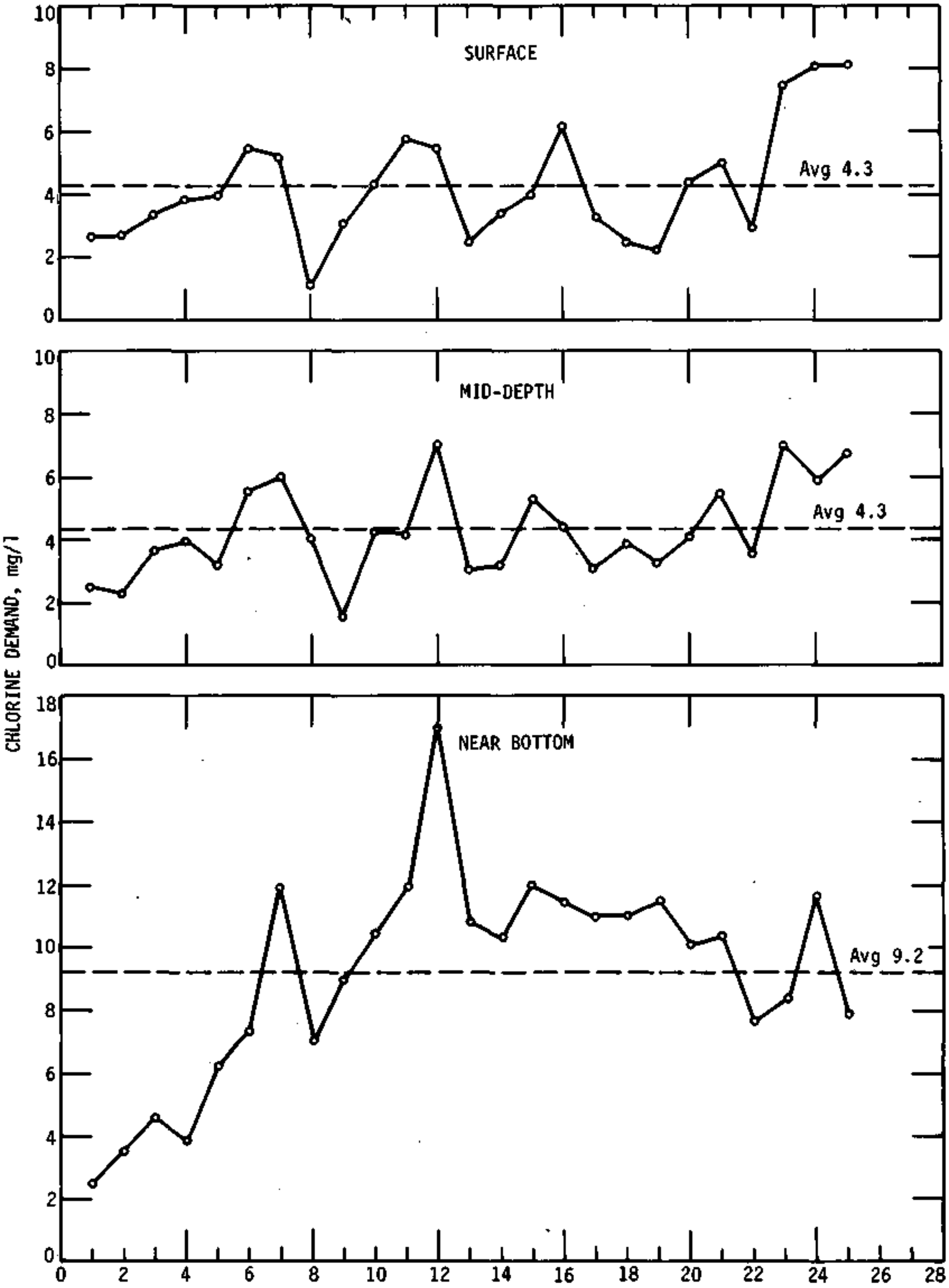


Figure 27. Chlorine demand at the surface, at mid-depth, and near the bottom of Lake Eureka

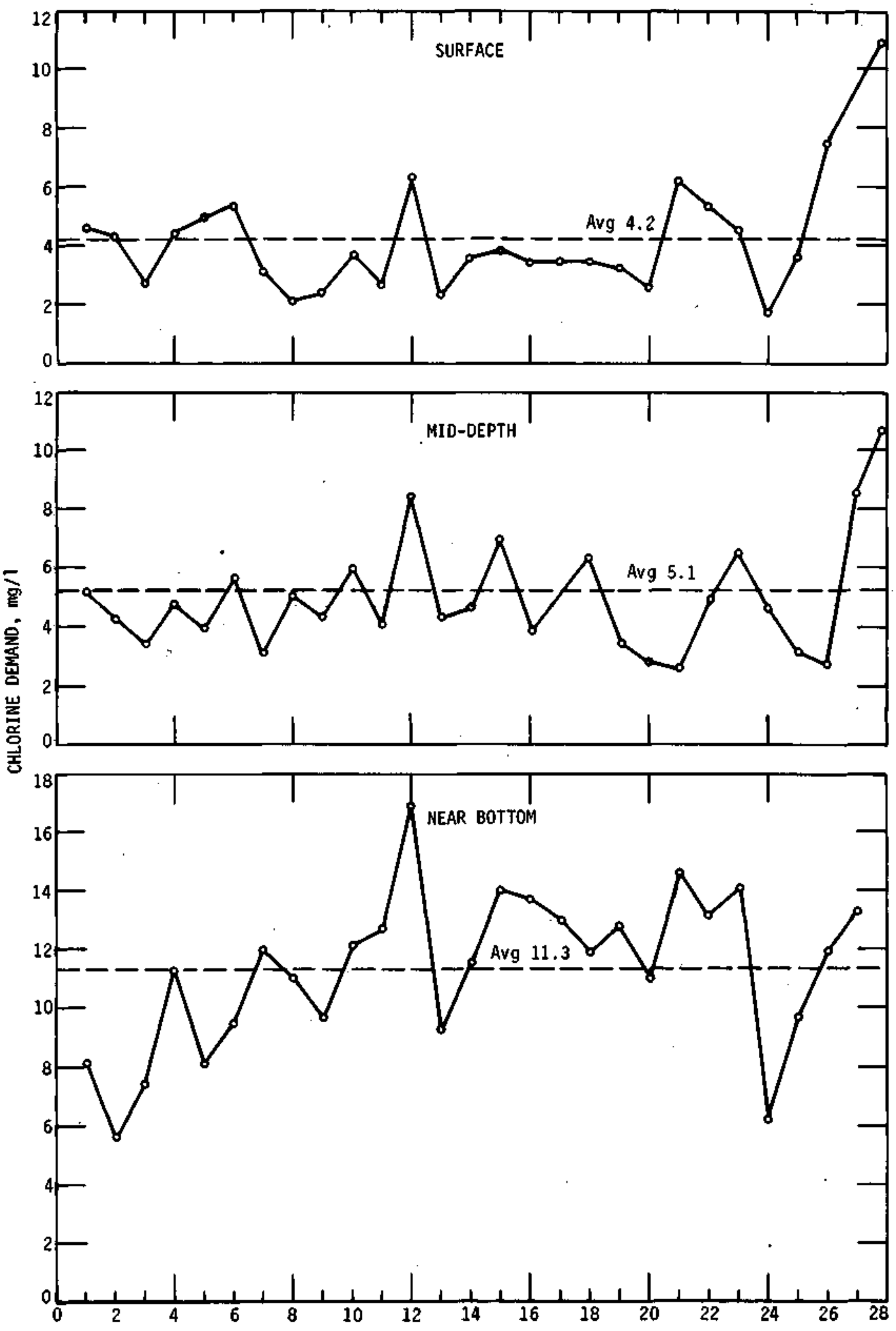


Figure 28. Chlorine demand at the surface, at mid-depth, and near the bottom of Lake Canton

A series of tests were performed in the laboratory as part of an effort to determine the relative chlorine demand of ferrous iron, manganous manganese, and sulfide ($S^=$). The same procedures were used on a series of dilutions with ferrous iron, manganous manganese, and sulfide concentrations in tap water to assess the chlorine demand. These tests indicated that manganous manganese did not impose a significant demand for chlorine within a 30-minute contact period. The relationships for ferrous iron and sulfide with chlorine demand were as follows:

$$Cl_2 \text{ demand} = 0.64\,(Fe^{++}) - 0.008 \qquad r = 0.99$$
$$Cl_2 \text{ demand} = 8.30\,(S^=) + 1.05 \qquad r = 0.99$$

On the basis of average chlorine demand for the bottom water strata of Lakes Eureka and Canton compared with the average soluble ferrous iron concentrations, it is estimated that 60 percent of the chlorine demand is due to ferrous iron concentrations in Lake Eureka but only 20 percent is due to ferrous iron at Lake Canton. The remainder of the chlorine demand is assumed to be due to sulfide, i.e., 40 percent for Lake Eureka and 80 percent for Lake Canton. These estimates suggest that the sulfide content of Lake Canton bottom waters is about three times that of Lake Eureka bottom waters.

In summary:

- The chlorine demand of the lake waters at the surface and at mid-depth did not differ significantly either within or between the lakes.
- The background chlorine demand at the water surface was 3.8 mg/1.
- The chlorine demand of the bottom waters of each lake differed from that of their overlying waters. The average chlorine demand of the bottom waters of Lake Eureka was 9.2 mg/1 compared with 11.3 mg/1 at Lake Canton.
- The rate of increase of chlorine demand in the bottom waters during the 12-week period April 17 to July 3 was 0.95 mg/1 per week at Lake Eureka and 0.75 mg/1 per week at Lake. Canton.
- The chlorine demand in Lake Eureka bottom waters is estimated to be due principally to ferrous iron. Sulfide concentrations impose the principal chlorine demand in Lake Canton bottom waters.

LAKE SEDIMENT DATA REDUCTION

A principal objective of the study was to identify distinguishable characteristics of the bottom sediments that influence the water quality of the overlying water. The previous discussion has shown that the physical and mineral characteristics of the bottom water strata differ considerably from those of the upper strata. This is suggestive of the important role lake bottoms play in governing a lake's overall water quality.

In addition to examining the sediments of each lake for moisture and organic content, iron and manganese concentrations, and macroinvertebrate communities, considerable reliance was placed on measurements for sediment oxygen demand. This was accomplished with varying degrees of success by *in-situ* measurements and a laboratory procedure. The initial work in Illinois on *in-situ* sediment oxygen demand was performed on the upper Illinois waterway by Butts (1974). Since that time *in-situ* measurements have been performed by the Water Survey at 119 stream locations in northeastern Illinois (Butts and Evans, 1978) and at 32 lake locations throughout the state (Kothandaraman et al., 1977; Butts and Sparks, 1977; Hill, 1978). Except for work done on the glacial lakes of the Fox Chain, all of the measurements have been performed in rather shallow water where aerobic conditions generally exist. This study was the first effort to examine the sediment oxygen demand of man-made impoundments.

Various procedures have been used to determine the oxygen demand of river and lake sediments. Bowman and Delfino (1978) have compiled an excellent review of the state of the art for field and laboratory procedures. For field purposes the Water Survey has relied upon the batch system. The equipment, described fully by Butts (1974) and Butts and Evans (1978), consists principally of a chamber respirometer equipped with a means of internally circulating water. The operating procedure involves trapping a volume of water in the chamber over a given bottom area and measuring the rate of dissolved oxygen drop with a galvanic cell oxygen probe implanted within the chamber.

A bell-shaped and a box-shaped chamber were used by the Water Survey in previous investigations but were found to be inadequate for the conditions encountered at Lakes Eureka and Canton. The production of gas from the two lake bottoms, not previously experienced in lake work, necessitated the design and fabrication of a pyramidal-dome chamber. The purpose of the dome was to provide adequate volume for the accumulation of gases to minimize the influence of the gases on the accuracy of the implanted dissolved oxygen probe. The unexpected problems with gas production coupled with the time constraint imposed by the contractual obligations of the study led to fewer data collections than originally intended. Nevertheless, from the sampling performed and the application of experienced judgment to the data, reasonable estimates of the relative sediment oxygen demands of the two lakes were achieved.

Because of the laborious efforts involved in *in-situ* sediment oxygen demand measurements, a laboratory procedure was devised during the study for estimating sediment oxygen demand. The basic steps involved the placement of a measured quantity of sediment in a BOD bottle under oxygenated conditions and measuring the rate of oxygen depletion at room temperature. The methodology is new for sediment work, so considerable effort was involved in testing its reproducibility as well as in using the testing procedure for identifying the various components of sediment oxygen demand. Details of the method will be discussed later.

There are differing opinions among workers as to the influential components of sediment oxygen demand, i.e., microbial versus macrofauna versus chemical. Butts and Evans (1978) concluded that microbial activity imposed the most influence in stream sediments. Neame (1975) reported that macrofauna accounted for only a small part of the oxygen demand in a lake. Butts and Sparks (1977) found that macrofauna was most influential in the oxygen demand of sediments in a pool of the Mississippi River. Brewer et al. (1977) reported that microbial activity might account for 91 percent of the sediment oxygen in Lake Hartwell, North Carolina, but Gardner and Lee (1965) reported the uptake of oxygen in Lake Mendota sediments was principally the result of chemical demand and proportional to concentrations of iron and sulfide.

Although the art of measuring sediment oxygen demand in water bodies requires more definitive procedures, it is not too early to consider adequate methods for identifying the proportion of the demand respectively due to chemical reactions and the respiratory activity of microbial and macrofauna communities. As part of the laboratory procedures during this study an effort was made to identify the components of oxygen demand in the sediments of Lakes Eureka and Canton.

The following discussion sets forth an evaluation of the sediment-related data collected during this study.

Table 8. Some Characteristics of Lake Sediment

	Moisture (%)	*Organic (%)*	*Total iron (ppm)*	*Total manganese (ppm)*
Lake Eureka				
4/26	66.0	8.6	41,040	1,002
6/1	66.5	8.7	39,890	840
6/15	70.0	9.0		
6/26	66.8	7.8	52,200	790
7/10	72.0	10.0	41,590	910
7/24	72.0	10.0	37,180	940
8/7	69.8	8.3	32,600	900
8/14	70.5	8.7	40,000	1,070
Average Concentrations	69.2	8.8	40,640	922
Lake Canton				
4/26	66.0	*23.0	47,170	1,460
5/26	46.3	6.9	48,200	1,180
6/15	71.0	8.0		
6/26	74.0	7.2	54,400	1,170
7/10	74.0	6.0	55,490	1,280
7/24	75.0		41,900	1,230
8/7	71.5	7.2	41,000	1,370
8/14	67.2	6.6	41,000	1,190
Average Concentrations	68.2	7.0	47,023	1,268

**Excluded from average calculation*

Table 9. Average Iron Content in Illinois Lake Sediments

	Iron (ppm)
Lake Canton	47,023
Lake Eureka	40,640
12 strip mine lakes	24,225
Cedar Lake watershed*	22,217
Rend Lake	19,200

**Cedar Lake, Little Cedar Lake, and Alto Pass Reservoir in Jackson and Union Counties.*

Sediment Characteristics

Samples of sediment were collected from each lake, independent of *in-situ* sediment oxygen demand measurements, on eight occasions. They were examined for moisture and organic (volatile solids) content as well as for concentrations of iron and manganese. The results are shown in table 8. On the average there was little difference between the sediments of the two lakes for moisture and organic content. The organic content in sediments averaged 8.8 percent at Lake Eureka and 7.0 percent at Lake Canton. However, the average iron and manganese content of the sediment in Lake Canton significantly exceeded that for Lake Eureka. Iron was about 6400 ppm higher and manganese was about 350 ppm higher.

A comparison of the average iron concentrations in the sediment of the two lakes with those of other impoundments in Illinois is shown in table 9. The sediments in the study lakes are substantially higher in metal content. It is possible that iron concentration in lakes is a function of age since the lakes offered for comparison with Lakes Eureka and Canton are rather recent creations. On the other hand, there may be regional differences in the lakes since most of those used for comparison are not located in the central part of the state as are Lakes Eureka and Canton.

The relative magnitude of the iron and manganese concentrations in the sediments of Lakes Eureka and Canton is reflected in the mud-water interface concentrations of the two lakes. The concentrations of the two metals are higher in the interface waters at Lake Canton than at Lake Eureka. As described previously, this is not the case for iron concentrations in the bottom waters. The average iron content of bottom waters in Lake Eureka is about twice that observed at Lake Canton.

In summary:

- There is little difference in the moisture and organic content of the sediments in the two lakes. The average moisture content ranged from 68.2 to 69.2 percent; the average organic content ranged from 8.8 to 7.0 percent.
- There is a difference between the two lakes in iron and manganese concentrations in the sediments. Iron averaged about 47,000 ppm in Lake Canton and about 40,600 ppm in Lake Eureka. Manganese averaged about 1270 ppm in Lake Canton and 920 ppm in Lake Eureka.
- The average iron content of the sediments of the study lakes was about twice the concentration observed in other Illinois impoundments. The differences may be a function of lake age or regional location.

Benthic Macroinvertebrates

Sediment samples for benthic macroinvertebrate examination were collected from the two lakes, independent of sediment *in-situ* measurements, at the deepest water depths. Six samples from Lake Eureka and seven samples from Lake Canton were collected. A sample consisted of three grab collections with a 6 X 6-inch Ekman dredge. Each sample was washed in the field through a U. S. Standard No. 30-mesh sieve bucket and preserved in 95 percent ethyl alcohol. In the laboratory the organisms were picked from the bottom detritus, identified, counted, and preserved.

Only three taxa were recovered from the sampling for aquatic macroinvertebrates. As shown in table 10 the communities in both lakes were dominated by the phantom midgefly larvae *(Chaoborus sp.)*. This organism has the capability of existing in anaerobic conditions because of its ability to migrate to the upper aerobic layers for occasional replenishment of oxygen. The midgefly larvae (Chironomidae) and aquatic worms (Tubificidae), the only other two macroinvertebrates recovered, do not thrive in anaerobic conditions. The number of macroinvertebrates found in Lake Canton substantially exceeded those recovered in Lake Eureka. The number of individuals per square meter obtained per collection ranged from 14 to 115 at Lake Eureka and from 244 to 8755 at Lake Canton. Presumably the physical nature of the bottom muds in Lake Canton provides a more suitable habitat for the phanthom midge larvae than that of Lake Eureka. since the overlying water quality at both lakes is equally hostile to the development of benthic communities.

The number and taxa of benthic macroinvertebrate collected at the two lakes were not unlike those obtained from the anaerobic zones in other Illinois lakes.

Table 10. Benthic Macroinvertebrates in Muds of Lakes at Maximum Water Depths

	Chironomidae (counts/m^2)	*Chaoborus (counts/m^2)*	*Tubificidae (counts/m^2)*	*Total (counts/m^2)*
Lake Eureka				
4/17	14	24	0	100
6/19	0	14	0	14
7/24	0	57	0	57
8/30	0	0	14	14
9/22	0	115	0	115
10/2	0	57	0	57
Lake Canton				
4/17	14	1851	14	1879
5/29	0	244	0	244
6/19	0	904	0	904
7/25	0	502	0	502
8/30	14	345	0	359
9/20	0	4119	0	4119
10/4	0	8755	0	8755

In summary:

- The phantom midgefly larvae *(Chaoborus sp.)* frequently made up 100 percent of the total population of benthic macroinvertebrates in the two lakes.
- Populations at Lake Canton were much greater, ranging from 244 to 8755 counts/m^2, than at Lake Eureka where they ranged from 14 to 115 counts/m^2.
- The density and taxa recovered in the two lakes were not unlike those found in the anaerobic zone of other Illinois lakes.

In-Situ Sediment Oxygen Demand

In-situ sediment oxygen demand (SOD) measurements were made at Lake Canton on six occasions and at Lake Eureka on five occasions. Three different types of respirator chambers were used. These devices, shown in figure 29, are from left to right the pyramidal-dome, bell, and box types. The device on the far right is a wooden prototype of the pyramidal-dome chamber fabricated during the study. Initial efforts were made with the box and bell chambers. As mentioned previously these units, which had been used successfully in other water bodies, were not of proper design to completely overcome the interference caused by gas production while performing measurements at Lakes Eureka and Canton.

The first runs with the box type produced reasonable results but during the second run results were erratic. The flat top of the box prevented the gas being emitted from the bottom muds from collecting within the chamber at a single point. Captured gas bubbles moved across the membrane of the oxygen probe causing pronounced peaks and valleys in the recordings of oxygen usage. Since the bell type, because of its configuration, seemed likely to minimize the gas problem it was tried at Lake Canton on May 26. Although the peaks and valleys did not occur, the flatness of the dissolved oxygen curve indicated the chamber did not function properly. These experiences led to the design and fabrication of the pyramidal-dome chamber.

The pyramidal-dome chamber is a box type with an interior gas deflector baffle designed to provide storage for the entrapped gases (see figure 30). The final design provided for an operational water volume capacity more than 200 percent greater than the bell and box samplers. Although the data obtained with the new device were considerably improved they still required definitive judgment for interpretation.

In the performance of field sediment oxygen demand measurements samples of the sediment were collected each time for moisture and organic assessment as well as for benthic macroinvertebrate densities. For moisture and organic analyses about 65 to 76 grams of an Ekman dredge sample was scraped from the top layer. The remainder of the sample was prepared and examined for benthic organisms as previously described.

The sediment oxygen demand curves recorded for each run were used to interpret the data. The rates of oxygen usage depicted by the curves are in units of milligrams per liter per minute (mg/l/min) and must be converted into grams per square meter per day (g/m^2 /day) for practical application. The formula for conversion is:

$$\mathrm{SOD} = (1440\ SV)/10^3\ A \qquad (6)$$

where

SOD = sediment oxygen demand, g/m^2 /day
S = slope of portion of curve, mg/l/min
V = volume of samplers, liters
A = bottom area of sampler, m^2

Generally, equation 6 is applied to the portion of a curve which is linear or approaches linearity. Many curves, especially those generated for polluted sediments, evolve into a straight line after the effects of initial bottom distrubances have subsided. Often this evolution is clear and distinct, but at other times it is not. Defining SOD curve forms or trends can be a valuable aid in data interpretation. Consequently all the curves were subjected to statistical regression

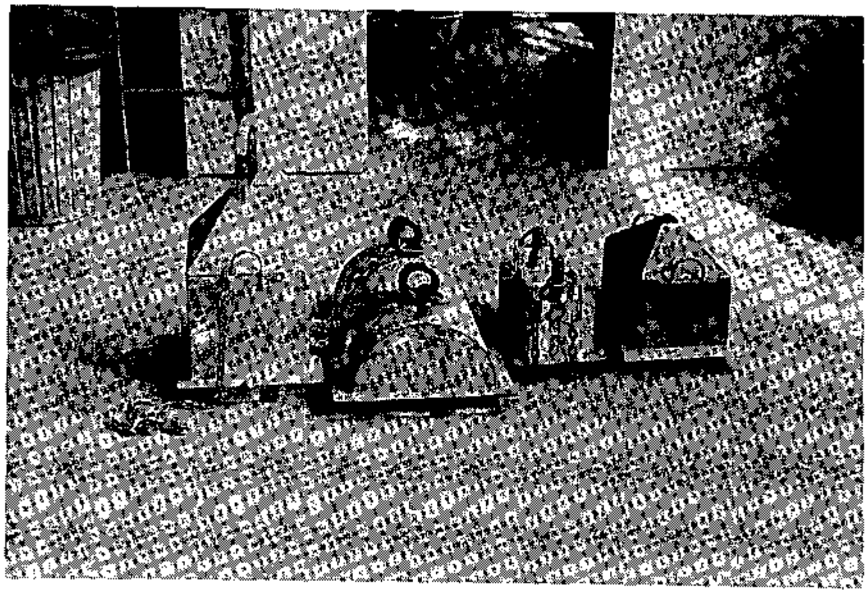


Figure 29. Three types of chamber respirometers used for *in-situ* sediment oxygen demand

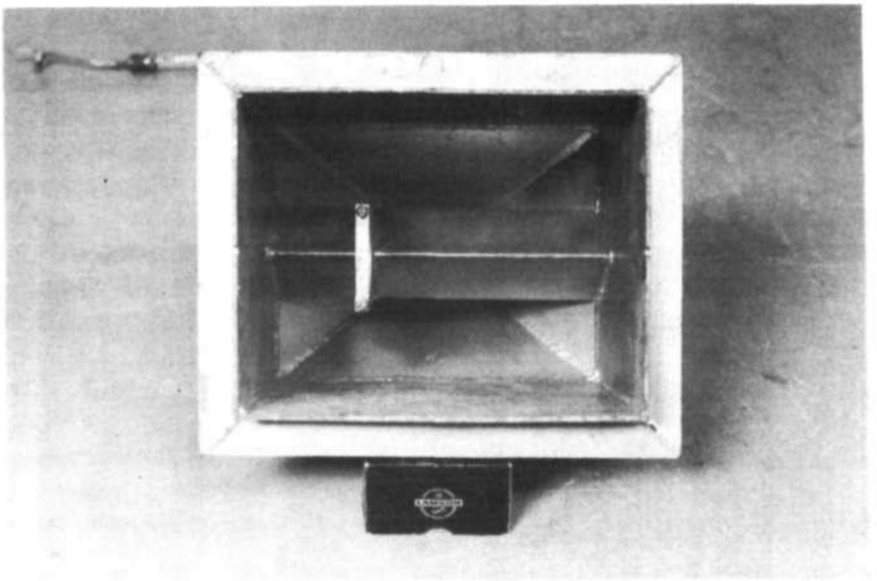


Figure 30. Bottom view of pyramidal-dome chamber showing gas deflector plates

equation fitting techniques. Linear, exponential, and log-log fits were made and compared using correlation coefficients and standard errors of estimate. The generalized curve fitting equations were:

$$\text{linear} \quad DO_{used} = a + bt \tag{7}$$

$$\text{semi-log} \quad DO_{used} = a \exp(bt) \tag{8}$$

$$\text{log-log} \quad DO_{used} = at^{b} \tag{9}$$

where

DO_{used} = dissolved oxygen in mg/l utilized over a time interval

t = minutes

a and b = regression constants

The *in-situ* SOD measurements, taken at ambient water temperatures, were corrected to 20 and 25° C for comparative purposes by the equation:

$$SOD_{T} = SOD_{20}(1.047^{T-20}) \tag{10}$$

where

SOD_{T} = SOD rate at any temperature, °C

SOD_{20} = SOD rate at 20°C

This equation is a form of the Arrhenius model widely used in water quality studies involving the stabilization of carbonaceous materials in aqueous environments.

The sediment oxygen demand expressed in terms of the standard areal rate units of g/m^2 /day can be converted to mg/l for a given segment or reach of water with the formula:

$$G' = 3.28\, Gt/H \tag{11}$$

where

G' = oxygen used, in mg/l

t = detention time per reach, in days

H = average water depth in the reach, in feet

Table 11. Best Estimate SOD Rates Derived from Observed Field Data

	Respirometer	SOD Rates ($g/m^2/day$) Ambient	SOD Rates ($g/m^2/day$) @ 25°C	Evaluation
Lake Canton				
4/14	Box	1.35	2.95	good
5/12	Box	2.19	4.36	poor
5/26	Bell	1.39	2.64	poor
6/29	Pyramidal-dome	4.30	8.18	fair
9/01	Pyramidal-dome	20.67	39.32	fair
10/24	Pyramidal-dome	23.59	41.31	fair
Lake Eureka				
4/14	Box	2.39	4.76	good
6/01	Box	4.35	8.66	poor
6/23	Pyramidal-dome	3.82	7.27	good
8/29	Pyramidal-dome	1.66	2.51	good
10/24	Pyramidal-dome	5.78	10.50	good

This formula has been developed on the assumption that the bottom area of the water body approximates the water surface area.

Because of the different types of devices and techniques used, resulting in poorer quality of dissolved oxygen usage curves than previously experienced, data interpretation was most difficult. In terms of confidence the estimates ranged from poor to good. Best computational estimates of *in-situ* sediment oxygen demand rates for the two lakes are given in table 11. With the values derived from the pyramidal-dome device, for which the results were evaluated as fair to good, the average for Lake Eureka was 6.76 $g/m^2/day$ compared with an average for Lake Canton of 29.6 $g/m^2/day$. The only other lakes in Illinois with similar water depths that have been examined by this technique are Pistakee Lake and Lake Catherine in the Fox Chain. The respective values observed in those water bodies were 31.6 and 12.98 $g/m^2/day$.

If the *in-situ* sediment oxygen demand procedures originally conceived had been successful, thus producing results that could be used reliably for computational purposes, they would have been applicable to the following concepts. Equation 11 can be used to estimate the rate of oxygen depletion in the water column of a lake, starting at the bottom, if it can be assumed that there is no migration of dissolved oxygen from overlying water strata having higher concentrations of dissolved oxygen. However, significant migration of dissolved oxygen does occur along a gradient. According to Casey and O'Connor (1978) the molecular diffusivity of dissolved oxygen in a quiescent bulk water remote from an air-water interface is the same as the diffusivity of dissolved oxygen through water immediately adjacent to the free air-water interface. Under these assumptions, dissolved oxygen transfer can occur by molecular diffusion within lake waters from a water stratum of higher dissolved oxygen concentration to a water stratum of lower dissolved oxygen concentration. The rate of transfer can be expressed as:

$$Q = f A (C_a - C_b) t \qquad (12)$$

where

Q = the oxygen load transferred from one water stratum to another as an areal rate, i.e., $g/m^2/day$

f = the velocity factor, in m/day

A = the interfacial area, in m^2

C_a = the dissolved oxygen above the interface, in g/m^3

C_b = the dissolved oxygen below the interface, in g/m^3

Using f as 6 mm per hour, as suggested by Casey and O'Connor,(1978), the following equation applies:

$$q = 0.144\,(C_a - C_b) \qquad (13)$$

where

q = the oxygen absorbed, in g/m^2 /day

Oxygen depletion can occur only when q is less than G^1, the oxygen used by the sediments. The term C_b is zero during the initial stages of oxygen depletion at the mud-water interface and as G^1 exceeds q it, too, becomes zero at some undefinable water-water interface.

The rate of DO depletion in the water column is related to the net effect of DO diffusion (downward) and DO usage due to SOD (upward). For example, on April 13 the average DO within 5 feet of the bottom of Lake Canton was 6.10 mg/1. The DO concentration at the upper interface (~ 6 feet from bottom) of the column was 7.90 mg/1 but 4 days later it was 6.20 mg/1. During this period the average C_a [(7.90 + 6.20)/2] was 7.05 mg/1. The C_b at the mud-water interface was 0.0. From equation 13, q is 1.02 g/m^2 /day. From table 11 the *in-situ* SOD on April 14 was 1.35 g/m^2 /day. The net oxygen usage therefore was 0.33 g/m^2 /day applied to the water column, i.e., (1.35 - 1.02). Substituting G = 0.33 g/m^2 /day, t = 4, and H = 5 feet in equation 11 yields G' = 0.87 mg/1. This is the oxygen used during the 4-day period in the 5-foot water column and should produce an average DO in the column of 5.23 mg/1 (6.10 - 0.87). The measured average was 5.38 mg/1. With the same methodology for estimating the average DO in the water column within 5 feet of the bottom, the computed value on April 18 was 5.07 mg/1 versus an observed average of 5.18 mg/1.

As previously discussed in detail in the assessment of dissolved oxygen in the lake waters, the rate of dissolved-oxygen-depleted water upward migration in the water column may be a distinguishable characteristic of a lake. The relationship of sediment oxygen demand to that rate of migration was a major objective of this study. Unfortunately the 'quality' of the *in-situ* sediment oxygen demand rates developed was not suitable for establishing this relationship.

In summary:

- *In-situ* sediment oxygen demand rates were not clearly defined mainly because of the unexpected difficulties from gas production in the lakes.
- A new chamber respirometer was designed, fabricated, and used with some success in the presence of gas emissions from bottom muds.
- Based solely on three samples derived from the new chamber on each lake, the average rate of sediment oxygen demand for Lake Eureka was 6.76 g/m^2 /day compared with an average for Lake Canton of 29.6 g/m^2 /day. These results are comparable to rates observed in two other Illinois lakes of similar depth.
- A methodology employing sediment oxygen demand rates has been outlined which can be useful in predicting the rate of ascent of dissolved-oxygen-depleted water in the water column of a lake during the development of an anaerobic zone.

Laboratory Sediment Oxygen Demand

Previous experience with *in-situ* sediment oxygen demand measurements in streams and lakes in Illinois indicated that an unrealistic amount of time and labor would be required to assess all lakes in the state by the methodology used. If such measurements could be made from samples of sediment delivered to the laboratory, where many determinations could be made in a relatively short time, the effort involved in examining a large number of lakes could be substantially reduced. These thoughts led to the development of a tentative laboratory procedure for determining the sediment oxygen demand of lake bottom muds. The following discussion outlines the evaluative procedures used and the results derived during the development of the procedure.

All sediment samples examined were obtained with an Ekman dredge and tested within 48 hours. Interim storage was in wide-mouth plastic bottles at 4° C. After the sample was mixed by an electric mixer, four portions each of four different weights (wet weights of approximately 0.5, 1.0, 2.0, and 3.0 grams) were transfered to 16 BOD bottles. The bottles were filled with oxygenated tap water and a self-stirring dissolved oxygen probe was inserted in the bottles one at a time. After about a 1-minute stabilization period the initial dissolved oxygen was recorded. The bottles were placed on a water-driven magnet stirrer arrangement and the contents of the bottles were mixed for 1 hour. Dissolved oxygen concentrations were then recorded. The difference between the initial dissolved oxygen and that measured after 1 hour of mixing was considered the dissolved oxygen consumed by the sediment. This is the basic procedure. In its development the effects of initial dissolved oxygen, reproducibility, sediment dosage, and biological and chemical quality were explored.

Some workers (Polak and Haffner, 1978; Edberg and Hofsten, 1973; Martin and Bella, 1971; McDonnell and Hall, 1969; Edwards and Rolley, 1965) support the view that the rate of sediment oxygen uptake is dependent upon initial dissolved oxygen concentrations. Other workers (Hargrove, 1-969; Fillos and Molof, 1972) report that oxygen uptake was independent of initial dissolved oxygen concentrations at least within the range of 2 to 5 mg/1. Bowman and Delfino (1978) generalized that the initial concentrations in the range of 3 to 8 mg/1 did not affect sediment oxygen demand rates.

For this study the initial oxygen levels examined ranged from 5.6 to 7.0 mg/1. The results of subjecting a sediment sample to three different levels of initial dissolved oxygen concentrations are shown in figure 31. The residual dissolved oxygen levels differ with time, but in terms of oxygen consumed the results are practically identical. In other words, the quantity of oxygen consumed is independent of initial levels between 5 and 7 mg/1. These results set the limits within which initial dissolved oxygen levels were maintained for the laboratory tests performed in this study.

For testing the reproducibility of the procedure, three to four replicates of sediment samples from various sources were used. The results are shown in figure 32. Although some variation is apparent, it is within the limits of experimental design. From these observations the procedures used are clearly reproducible.

Preliminary observations indicated that the larger the sediment dosage introduced into the BOD bottle, the greater the oxygen consumption. This is demonstrated in figure 33a. However, there was not a proportional increase in oxygen consumption commensurate with a corresponding proportional increase in the sediment dosage. This difference is depicted in figure 33b. The implication from these observations is that there must be a limit to the quantity of sediment that can be effectively exposed to dissolved oxygen in the container. It was concluded that the sediment dosage. for the testing equipment used, should be limited to 3 grams wet weight or less than 2 grams dry weight.

Measurements of oxygen consumed were usually for an 8-hour period for all sediments assayed. During the assessment of each lake sediment four replicates each of four different weights were run simultaneously in 16 BOD bottles. The pertinent data are given in Roseboom et al., 1979. Though the runs were for 8 hours, the rate of oxygen consumption occurring during the first hour, the maximum rate, was used to express the sediment oxygen demand rate. The sediment oxygen demand rate is expressed as the milligrams of oxygen consumed per gram weight of dry sediment in 1 hour (mg O_2 /g/hr). The results of typical runs are shown in figure 34.

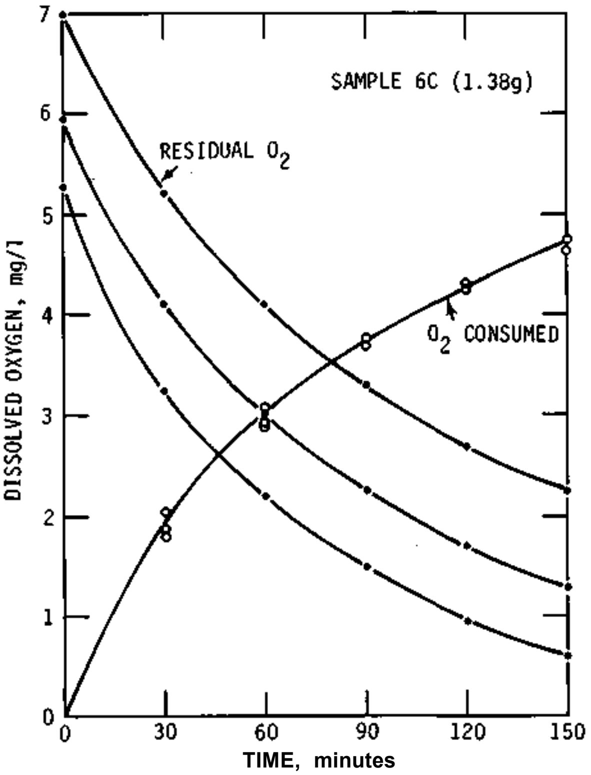


Figure 31. The effects of initial dissolved oxygen levels on oxygen consumed by sediments

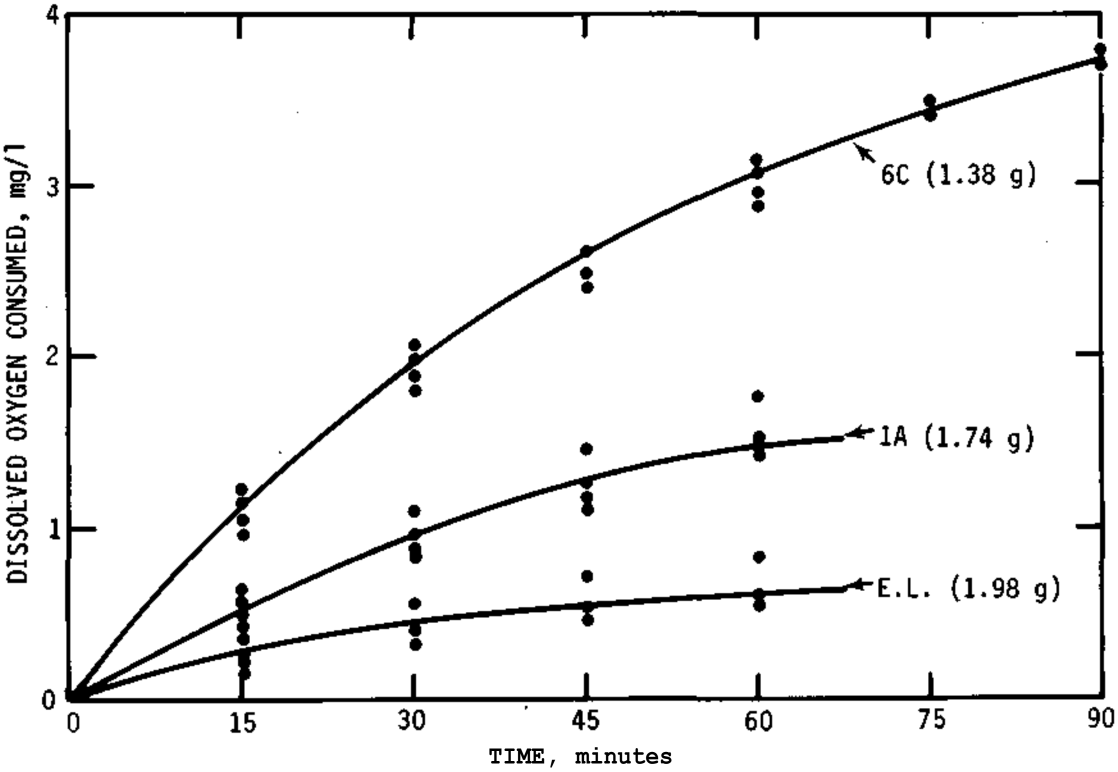


Figure 32. Reproducibility of sediment oxygen demand tests

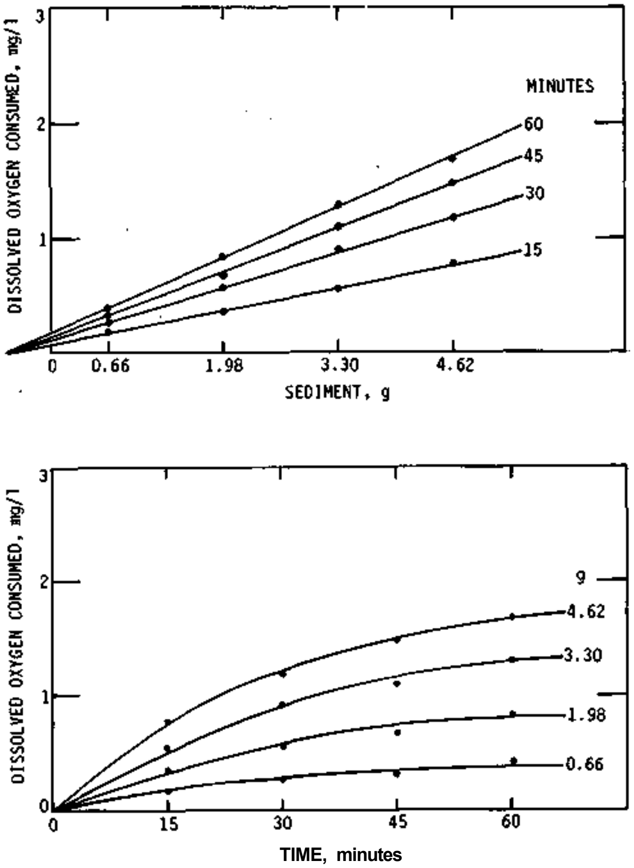


Figure 33. Relationship of oxygen consumed and amount of sediment dosage introduced

Eleven sediment samples from Lake Eureka and 13 samples from Lake Canton were assessed. Between 6 and 7 sediments from four other lakes were also examined. These were Horseshoe, Decatur, Catherine, and Channel Lakes. The results are summarized in table 12. The oxygen demand of the sediments at Lakes Canton and Eureka generally conformed to the seasonal cycle, i.e., lower in the spring, higher in the summer, and lower in the fall. The range for Lake Canton was about 0.7 to 1.5 mg O_2 /g/hr, while that for Lake Eureka was about 0.7 to 1.2 mg O_2 /g/hr. The average for Lake Canton was 1.20 mg O_2 /g/hr; that for Lake Eureka was 0.96 mg O_2 /g/hr.

In comparing the data for all lakes, that for Horseshoe Lake was the highest averaging 1.81 mg O_2 /g/hr. The interest in Lake Catherine was prompted by the installation of an aeration device on its bottom with the expectations of reversing existing anaerobic conditions. As shown in table 12, two measurements prior to the operation of the unit followed by several measurements after a period of operation suggest that some reduction and, indeed, stabilization of the oxygen demand of the sediments might be achieved.

The components of the oxygen demand of the sediments handled in the laboratory are microbial and chemical. Through the use of a salt solution as a bactericide and the method of additions using ferrous iron, it was found that most of the demand for oxygen by anoxic sediments obtained from Lakes Eureka and Canton is derived from chemical demand. From the examination of three sediment samples gathered at Lake Eureka, the proportion of the total oxygen demand

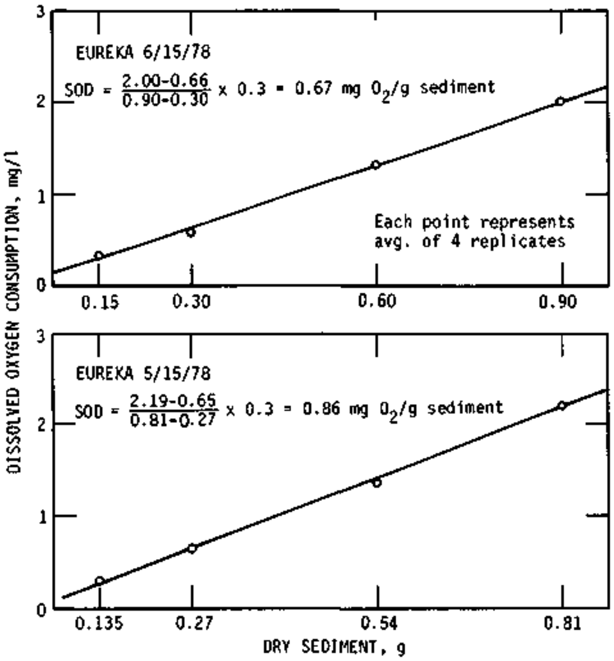


Figure 34. Typical data and computations for determining sediment oxygen demand rates

Table 12. Laboratory Sediment Oxygen Demand for Six Illinois Lakes
(SOD in mg 0, /g/hr)

	Lake Canton	*Lake Eureka*	*Horseshoe Lake*	*Lake Decatur*	*Lake Catherine*	*Channel Lake*
5/15/78	0.65	0.86				
6/15/78	0.78	0.67				
6/21/78			2.00			
6/26/78	1.50	0.71		0.48	0.65	0.42
7/5/78			1.60			
7/10/78	1.14	0.84			0.93	0.42
7/18/78			1.65	0.56		
7/24/78	1.23	1.07		0.55	0.50*	0.37
8/2/78			1.94			
8/7/78	1.35	0.99		0.54	0.44	0.56
8/14/78	1.02	1.00	1.76			
8/22/78				0.59	0.56**	0.43
9/20/78	1.32	1.07			0.44	0.42
9/25/78	1.48	1.19		0.58		
10/2/78	1.36	1.17				
10/11/78	1.32	1.02				
10/16/78	1.26		2.30			
10/24/78	1.17		1.42			
Average	1.20	0.96	1.81	0.55	0.59	0.44

**Aerator started*
***$CuSO_4$ treatment*

attributable to ferrous iron ranged from 67 to 96 percent. Liu (1973) has suggested that the oxygen demand at the undisturbed surface of a lake bottom may be predominantly of biological origin, whereas that portion of the sediment below the surface imposes mostly a chemical demand. Thus the manner in which sediment is collected and subsequently handled may influence the nature of the oxygen demand in the laboratory.

As part of the study an initial step was made toward developing a flow-through method for ascertaining the oxygen demand of sediments. The procedure is similar to *in-situ* measurements and work is continuing in its development.

In summary:

- A batch method employing BOD bottles was developed for determining the relative rates of sediment oxygen demand of lake muds. The procedure is reproducible, inexpensive, and simple.
- Rates of sediment oxygen demand for Lake Eureka were less than for Lake Canton with an average of 0.96 versus 1.20 mg O_2 /g/hr, respectively.
- The sediments of six Illinois lakes were subjected to the test procedures and average rates of demand varied from 0.44 to 1.81 mg O_2 /g/hr.
- The major component of oxygen demand was chemical with ferrous iron being the principal oxygen demanding agent.

COMMENTARY AND CONCLUSIONS

This study was undertaken with two basic premises in mind. First, there is a necessity to view man-made impoundments in Illinois as special bodies of water which may not conform, in their manifestations of eutrophy, to the schemes of classical limnology. Secondly, the role of oxygen in the biological economy of water, its relation to the processes of aerobic and anaerobic decomposition, its influence on the chemical equilibria, and its part in the solution of metals, pesticides, nutrients, and gases make it —whether absent or present —the most important regulator of the eutrophic conditions of a lake system. On the basis of these tenets, developed from previous experience on Illinois lakes, consideration must be given to that locale of man-made impoundments where the influences governing water quality are paramount —the lake bottom and the mud-water interface.

It is not enough to view the water surface of a lake and judge its health. In lakes in Illinois there are insidious perturbations occurring below the placid water surface. A better understanding of the influencial extent and mechanism of these bottom-meditated reactions will lead to a more realistic appraisal of a lake's eutrophic condition. More realistic appraisal procedures will, in turn, provide the basis for rational water quality restoration techniques applicable to lake systems in Illinois. The lake bottom may be remote from the water surface in one case and close to the surface in another case. Under either condition the quality of the overlying waters will be significantly influenced by the lake bottom —by either physical disbursement, biological activity, chemical reactions, or by all three modes simultaneously.

It is fair to state that the basic objectives of the study were achieved. The magnitude and sources of significant oxygen demand within a lake system were measured and identified. Rates of oxygen reduction during the formation of the anaerobic zone were computed, and certain techniques were developed that can be useful for comparing the oxygen demand potential of one lake's bottom strata with another's. It is equally fair to say that these techniques are in their infancy of development. Much work remains to be done toward developing procedures that will be useful to the practitioner who is being required to make decisions now, and who does not have the time for long term data collection and tedious evaluation sessions.

The following discussion will examine those features that Lakes Eureka and Canton have in common as well as the differences identified during this study in productivity, water chemistry, and sediment oxygen demand. Both lakes were constructed to serve as a source of public water supply. In addition they are used for recreational purposes. Both lakes thermally stratify and form anaerobic zones in their bottom strata. Lake Eureka's thermal stratification regime is weak, presumably because of its shallow depth, whereas that of Lake Canton is well defined. The laboratory sediment oxygen demands, which do not differ very much for each lake, averaged 0.96 mg O_2 /g/hr for Lake Eureka and 1.20 mg O_2 /g/hr for Lake Canton. Ammonia concentrations in the bottom waters of both lakes were frequently in excess of 5 mg/1 during periods of stagnation. Such concentrations occurred earlier in the year at Lake Eureka, starting in August and persisting until October. Ammonia concentrations at Lake Canton reached a peak in September and persisted until the fall turnover. However, once the concentrations were established, differences between the two lakes were not distinguishable.

What about the differences between the lake systems? In terms of productivity in the two systems several aspects must be considered. The waters of both lakes support blue-green algae blooms. However, during the study period the *density* of algae at Lake Canton exceeded similar populations at Lake Eureka. On the other hand, the rate of alkalinity reduction at the water surface of Lake Eureka exceeded that of Lake Canton by 30 percent. A reasonable interpretation of this observation is that, though the algal density in terms of cells per milliliter may be greater in Lake Canton, the biomass per unit volume in Lake Eureka may be higher than in Lake Canton. This is speculation not confirmed by measurement. However, the potential for productivity is much higher at Lake Canton than at Lake Eureka if the phosphorus content of the bottom waters are considered. At Lake Canton the concentrations of total phosphorus in the bottom waters averaged 0.32 mg/1 compared with an average of 0.12 mg/1 at Lake Eureka. Also, the dissolved phosphorus at Lake Canton makes up about 52 percent of the total phosphorus versus 28 percent at Lake Eureka. From the data gathered, it appears that Lake Canton will be subject to more problems associated with nuisance algal blooms than Lake Eureka.

The waters of both lakes maintain anaerobic zones during a 5-month period in the summertime. About 14 percent of the water volume of Lake Eureka was void of oxygen during that period; 30 percent of Lake Canton's water volume was equally void of oxygen. The rates of oxygen reduction in the lower water strata during the formation of the anaerobic zone at Lake Eureka varied from 0.4 to 0.5 mg/1 per day; at Lake Canton it varied from 0.22 to 0.34 mg/1 per day.

In Lake Eureka the rise of oxygen-depleted water in the water column was at a rate of 0.7 feet per day during the formation of the anaerobic zone, and the extent of the anaerobic zone from the bottom was about 6 to 8 feet. At Lake Canton the rates were lower varying from 0.22 to 0.34 mg/1 oxygen reduction in the lower water layers with oxygen-depleted water rising in the water column at a rate of about 0.4 feet per day. The extent of the anaerobic zone from the bottom was 14 to 20 feet.

In essence the rate of anaerobic zone formation was greater at Lake Eureka but its extent from the bottom was less. On the average, the depth of the water (as measured from the surface) containing measureable quantities of dissolved oxygen during the period of stagnation varied from 10 to 12 feet at Lake Eureka and 11 to 17 feet at Lake Canton. This was the situation despite the fact that the average water depth of Lake Eureka was 16 feet and that at Lake Canton was 31 feet. On the basis of the extent of oxygen depletion in the two lakes, those conditions in Lake Canton are the most severe.

Significant quantities of iron and manganese are released from the bottom muds of both lakes during the stagnation period. Iron reached peak concentrations of 31.4 and 92.0 mg/1, respectively, in the mud-water interface of Lakes Eureka and Canton. However the average iron concentration in the bottom.waters of Lake Eureka was 4.85 mg/1; that for Lake Canton was 2.27 mg/1. Manganese reached peaks of 7.82 and 16.84 mg/1 in the two lakes. The iron is mainly in ferrous (Fe^{++}) form. The manganese is principally in the manganous (Mn^{++}) form. Iron and manganese migrate up the water column and the limit of that migration is the extent of the anaerobic zone. As in the case of phosphorus concentrations, the potential for elevated concentrations of Fe^{++} and Mn^{++} in the water was greater in Lake Canton. But the concentrations of iron in the bottom 2 feet of lake waters at Lake Eureka were higher than those at Lake Canton. Presumably this is due to some tendency toward mixing in the lower strata of Lake Eureka, as evidenced by the gradual increase in water temperature at the bottom during the period of stagnation.

The chlorine demand of the lake waters is a measure of the existence of readily oxidizable organic matter and inorganic minerals in the reduced state. The chlorine demand of bottom waters at Lake Eureka averaged 9.2 mg/1 compared with 11.3 mg/1 at Lake Canton. On the basis of laboratory tests it was estimated that ferrous iron was the principal component of chlorine demand at Lake Eureka while sulfides imposed the principal demand at Lake Canton. On an overall basis those substances in the lake waters reacting to the chlorine demand were in higher concentrations in Lake Canton.

The iron and manganese concentrations of the bottom muds were substantially higher at Lake Canton. The averages for the lake were 47,000 and 1,270 ppm, respectively, compared with the muds of Lake Eureka which averaged 40,600 ppm iron and 920 ppm manganese. These concentrations are about two times that observed in other Illinois impoundments.

From the best estimates gained from *in-situ* sediment oxygen demand measurements the average demand at Lake Eureka was 6.76 g/m^2 /day compared with 29.6 g/m^2 /day at Lake Canton.

The relative eutrophy of each lake, based upon the measurements performed both directly and indirectly, is summarized for comparative purposes in table 13. With the exception of transparency, all of the measurements designated in the table relate to bottom conditions.

It is clear that conditions are worse in Lake Canton than in Lake Eureka. Possibly an important factor is water depth which may govern the extent and duration of the anaerobic zone. This condition suggests that lakes may be classified, to a considerable extent, by mean water depth.

In terms of *rates* of dissolved oxygen reduction in the water strata, rise of oxygen-depleted water in the water column, alkalinity increase in the bottom waters, anaerobic zone development, increase in iron, and chlorine demand in bottom waters, those at Lake Eureka exceeded those at Lake Canton. The significance of the rates of reaction or development were not apparent in the overall assessment included in table 13. This lack of agreement suggests, too, that water depth is a factor. It is very likely that for lakes of near equal water depth *rate measurements* will be determining agents for classifying systems. Techniques to obtain these measurements that are less time consuming and more precise remain to be developed. Hopefully this study will encourage more work in that direction for conditions in Illinois lakes.

Table 13. Relative Eutrophy of Lakes Eureka and Canton

	Lake Eureka	*Lake Canton*
Transparency	−	+
High nuisance algae occurrence (including potential)	+	−
Dissolved oxygen deficiency	+	−
Iron (water)	−	+
Iron (interface)	+	−
Manganese (water)	0	0
Manganese (interface)	+	−
Ammonia (water)	0	0
Phosphorus (water)	+	−
Phosphorus (interface)	+	−
Cl_2 demand (water)	+	−
Sulfide (water)	+	−
Iron (sediment)	+	−
Manganese (sediment)	+	−
Benthic organism (deep)	−	+
In-situ sediment oxygen demand	+	−
Laboratory sediment oxygen demand	0	0

Note: + = less eutrophication; − = more eutrophication; 0 = equal eutrophication

REFERENCES

American Public Health Association, American Water Works Association, and Water Pollution Control Federation. 1975. *Standard methods for the examination of water and wastewater.* American Public Health Association, Inc., 1740 Broadway, New York, NY 10019, 1193 p., 14th edition.

Bortleson, G. C, and G. F. Lee. 1974. *Phosphorus iron and manganese distribution in sediment cores of six Wisconsin lakes.* Limnology and Oceanography v. 19:794-801.

Bowman, G., and J. J. Delfino. 1978. *Sediment oxygen demand techniques: A review.* University of Wisconsin Center for Health Sciences, State Laboratory of Hygiene, Environmental Sciences Section, Technical Report ES 78-1.

Brewer, W. S., A. R. Abernathy, and M. J. B. Paynter. 1977. *Oxygen consumption by freshwater sediments.* Water Research v. 11:471-473.

Butts, Thomas A., Jack W. Williams, and Ralph L. Evans. 1976. *Water quality evaluation of the Rector Creek - North Fork Saline River drainage basin.* Prepared for Soil Conservation Service USDA, by the Illinois State Water Survey, 95 p.

Butts, Thomas A., and Ralph L. Evans. 1978. *Sediment oxygen demand studies of selected northeastern Illinois streams.* Prepared for Northeastern Illinois Planning Commission. Illinois State Water Survey Circular 129, 177 p.

Butts, T. A., and R. E. Sparks. 1977. *Sediment oxygen demand-fingernail clam relationships in Mississippi River, Keokuk Pool.* Paper presented at the 1977 joint meeting of the Illinois State Academy of Science and Missouri Academy of Science, University of Missouri, St. Louis.

Butts, T. A. 1974. *Sediment oxygen demand in the upper Illinois waterway.* Illinois State Water Survey Report of Investigation 76, 32 p.

Casey, T. J., and P. E. O'Connor. 1978. *New light on mechanism of air-water oxygen exchange in quiescent systems.* Water Research v. 12:649-654.

Cowen, Peter A., V. Dean Adams, and Donald B. Porcella. 1976. *Iron dynamics in a gas-water sediment microcosm.* Utah Water Research Laboratory, Utah State University, *96* p.

Delfino, Joseph J., and G. Fred Lee. 1968. *Chemistry of manganese in Lake Mendota, Wisconsin.* Environmental Science and Technology v. 12:1094-1100.

Delfino, Joseph J., and G. Fred Lee. 1971. *Variations of manganese, dissolved oxygen and related chemical parameters in the bottom waters of Lake Mendota, Wisconsin.* Engineering Experimental Station Reprint No. 1551, University of Wisconsin.

Edberg, N., and B. V. Hofsten. 1973. *Oxygen uptake of bottom sediments studied in-situ and in the laboratory.* Water Research v. 7:1285-1294.

Edwards, R. W., and H. L. J. Rolley. 1965. *Oxygen consumption of river muds.* Journal of Ecology v. 53:1-19.

Fillos, J., and A. H. Molof. 1972. *Effects of benthic deposits on oxygen and nutrient economy of flowing waters.* Journal Water Pollution Control Federation v. 44:644-662.

Gardner, W., and G. F. Lee. 1965. *Oxygenation of lake sediments.* International Journal of Air and Water Pollution v. 9:553-564.

Hargrove, B. T. 1969. *Similarity of oxygen uptake by benthic community.* Limnology and Oceanography v. 14:801-805.

Hill, Thomas. 1978. Personal communication regarding study of Horseshoe Lake.

Illinois State Water Survey. 1978. *Water quality assessment of Rend Lake and its tributaries.* Prepared for Greater Egypt Regional Planning and Development Commission by the Water Quality Section, Peoria, 83 p.

Kothandaraman, Veerasamy, and Ralph L. Evans. 1975. *Annual temperature variations in an impoundment in central Illinois.* Journal American Water Works Association v. 10:639-642.

Kothandaraman, V., R. L. Evans, N. G. Bhowmik, J. B. Stall, D. L. Gross, J. A. Lineback, and G. B. Dreher. 1977. *Fox Chain of Lakes investigation and water quality management plan.* Cooperative Resources Report 5, Illinois State Water Survey, Illinois State Geological Survey, Urbana, 200 p.

Lin, Sundar. 1978. Personal communication. Illinois State Water Survey.

Liu, D. 1973. *Application of the manometric technique in the study of sediment oxygen depletion.* Canadian Research and Development v. 6:35-37.

Martin, D. C, and D. A. Bella. 1971. *Effect of mixing on oxygen uptake rate of estuarine bottom deposits.* Journal Water Pollution Control Federation v. 43:1865-1876.

McDonnell, A. J., and S. D. Hall. 1969. *Effect of environmental factors on benthic oxygen uptake.* Journal Water Pollution Control Federation v. 41:R353-R363.

Morgan, J. J., and Werner Stumm. 1965. *The role of multivalent metal oxides in limnological transformations as exemplified by iron and manganese.* Sanitary Engineering Reprint No. 75, Division of Engineering and Applied Physics, Harvard University.

Morton, S. D., and T. H. Lee. 1974. *Algal blooms - possible effects of iron.* Environmental Science and Technology v. 8:673-674.

Neame, P. A. 1975. *Oxygen uptake of sediments in Castle Lake, California.* Verhandlungen International Vereinigung Limnology v. 19:792-799.

Polak, J., and G. D. Haffner. 1978. *Oxygen depletion of Hamilton Harbour.* Water Research v. 12:205-215.

Roseboom, Donald P., Ralph L. Evans, and Thomas E. Hill. 1978. *Water quality in Cedar Lake and the relevance of its watershed.* Prepared for Greater Egypt Regional Planning and Development Commission by the Water Quality Section, Illinois State Water Survey, Peoria, 93 p.

Roseboom, D. P., R. L. Evans, W. Wang, T. A. Butts, and R. M. Twait. 1979. *Classifying Illinois impoundments: An examination of techniques for assessing lake bottom conditions.* Contract Report 215, Illinois State Water Survey, Urbana, 155 p.

Sullivan, William T. 1967. *Chemical composition of the mud-water interface zone with the description of an interface sampling device.* Proceedings, 10th Conference on Great Lakes Research, pp. 390-403.

Sullivan, W. T., and D. L. Hullinger. 1969. *Phosphates in Peoria Lake, a quantitative and qualitative evaluation of a nutrient in natural waters.* Transactions of the Illinois Academy of Science v. 62:198-217.

Wang, Wun-cheng. (1975). *Chemistry of mud-water interface in an impoundment.* Water Resources Bulletin, American Water Resources Association v. 4:666-675.