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Sediment Oxygen Demand in a Shallow Oxbow Lake

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CONTENTS

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ABSTRACT

In-situ sediment oxygen demand (SOD) measurements were made during the summer-fall of 1978 in Horseshoe Lake (in the Mississippi River flood plain) in conjunction with a water quality sampling program. This report presents only the findings of the SOD investigation. Sediments throughout Horseshoe Lake exert a significant oxygen demand on the overlying water, with the highest demands in dead zones of the lake. The sediments on the basis of SOD rates alone can be classed as moderately polluted. Bacteria and other microorganisms are the principal cause of the demand; macroinvertebrates cause about 1 percent or less. The primary productivity of the lake is very high and algal fallout may be a significant contributor to SOD. Dissolved oxygen in the lake is rapidly depleted in the absence of surface aeration or photosynthetic oxygen production. A simple mathematical model developed and verified to predict DO concentrations under warm, quiescent, dark conditions indicates that only about 36 hours would be needed to totally deplete DO under these conditions. The information generated by this study provides a good base from which to evaluate the degraded conditions of the sediments and the effects of these sediments on the oxygen resources of the lake.

INTRODUCTION

Sediment oxygen demand (SOD) measurements were made during the summer and fall of 1978 in Horseshoe Lake, an oxbow lake occupying the flood plain of the Mississippi River northeast of East St. Louis, Illinois. The general location and the areal layout of the lake are presented in figure 1. The lake level can be controlled at the outlet channel near its juncture with the Cahokia Canal by underflow sluice gates in conjunction with a fixed elevation overflow spillway. With the water surface elevation level with the spillway crest, the average lake depth is approximately 2 feet except for a small area shown on the map where sand and gravel are being hydraulically mined. In this area, the depth is approximately 50 feet.

The areal integrity of the lake has been severely changed by man in recent years. A portion of the lake has been leveed off for use as settling lagoons for treating Granite City Steel Company industrial wastes. The lake has also been bisected at three locations by causeways — two accommodate the passage of a railroad across the lower legs of the lake, and the third provides automobile access to Walkers Island.

A man-made outlet channel has provided a means by which flood flows from the Cahokia Canal can be diverted into the lake for storage by the manipulation of Tainter gates located in the canal below the outlet channel. The diverted water is heavily laden with silt, and deposition in the lake has resulted in the formation of an isthmus at the lower end of Walkers Island and an overall lowering of the storage capacity of the lake. The top layer of bottom sediments throughout most of the main body of the lake are basically unconsolidated and are easily suspended when mechanically disturbed. The surface area of the lake under normal conditions is approximately 2535 acres, including Canteen Lake and approximately 335 acres encompassed by the lagoon levee.

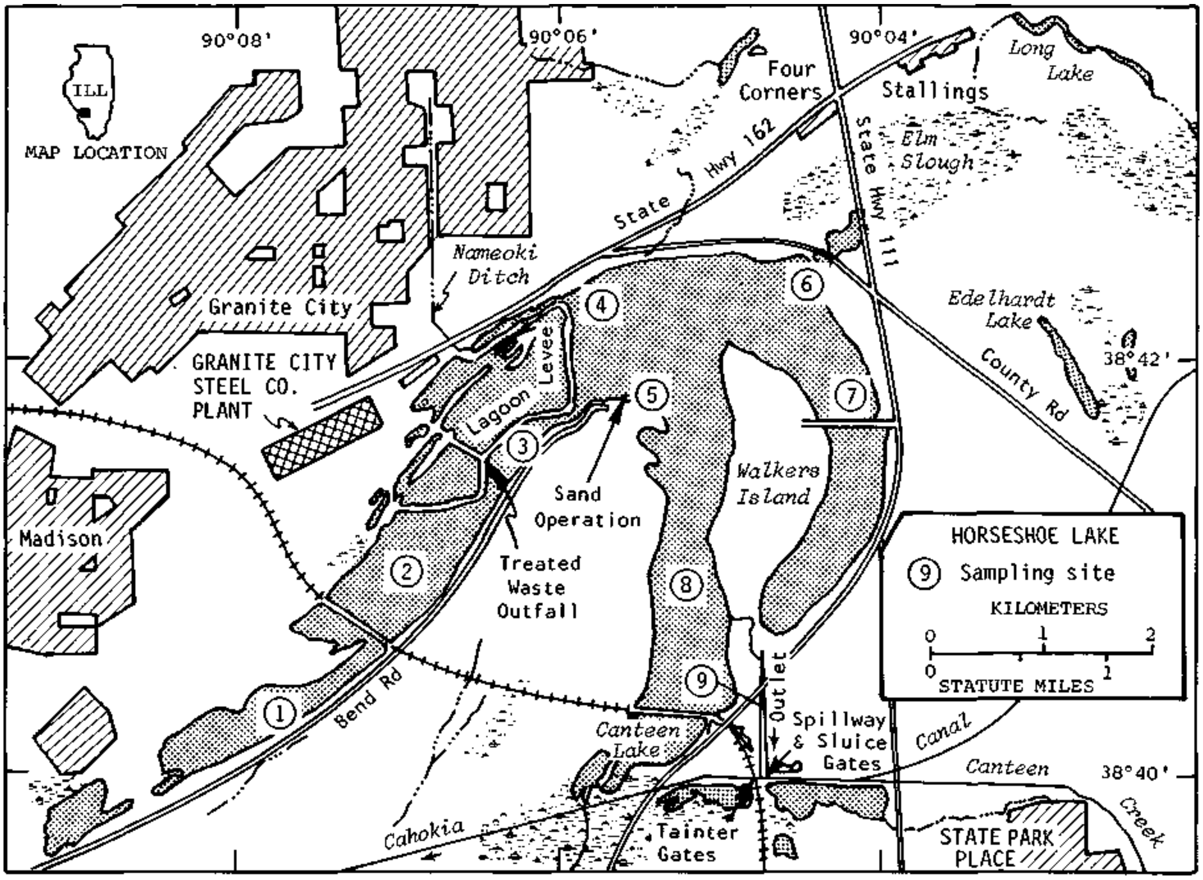

Figure 1. Location and areal layout, Horseshoe Lake

The Illinois Department of Conservation owns about one-third of the lake including a strip along the north shore beginning at the levee and all the area east of Walkers Island. The rest is privately owned. The lake is used for flood water retention, sand and gravel mining, waterfowl hunting, commercial and recreational fishing, and industrial waste assimilation. In state-owned areas, the use of boats is restricted to the waterfowl hunting season.

Because of a need for additional recreational land and water in the metropolitan St. Louis-East St. Louis area, consideration is being given by the Department of Conservation to expand the development of the lake for public use. Additional acquisitions of private holdings are being contemplated.

The lake historically has experienced water quality problems. Fourteen fish kills have been reported since 1959 with the most recent one observed in March 1979. The lake appears to be incapable of sustaining a healthy bass-bluegill fishery; however, a viable channel catfish fishery still exists.

The industrial waste discharge from the steel mill has been reduced to 25 million gallons a day (mgd) from a high of 68 mgd in June 1977. The waste treatment facilities are routinely meeting Illinois Environmental Protection Agency effluent standards.

The Illinois State Water Survey conducted a water quality sampling program under the sponsorship of the Department of Conservation to. aid in assessing proposed plans for further development of the area for public recreational use. Water quality sampling stations were established at nine locations as shown on figure 1. Sediment oxygen demand measurements were made at stations 2, 3,4, 7, and 8 on three occasions —June 27-28, August 30-31, and October 25-26, 1978. Water quality sampling was conducted biweekly from May 25, 1978, through January 23, 1979. This report is limited solely to presentation of the findings and conclusions related to the SOD investigative phase of this study. Sediment oxygen demand measurements can greatly aid in assessing the polluted nature of stream and lake bottoms and can aid in evaluating water quality problems.

SOD Definition

Sediment oxygen demand can be broadly defined as the usage of dissolved oxygen in the overlying water by benthic organisms. In some instances, it could include or be the result of inorganic chemical oxidation reactions. However, under aerobic conditions it is principally the result of the biochemical oxygen demands of micro- and macro-organisms. The major microdemand is due to bacteria; however, diatoms, protozoa, and aquatic fungi respiration can be significant at times. Macrodemand is caused by aufwuch communities (surface living organisms) and burrowing fauna. Worms, insect larvae and nymphs, leaches, and mussels are the principal burrowing types. Periphyton, or organisms which are attached to underwater substrates, represent an important source of SOD in some streams, in some deep areas of clear lakes, and in the littoral zones of most lakes.

Acknowledgments

This study was conducted as part of the work of the Water Quality Section of the Illinois State Water Survey, Dr. William C. Ackermann, Chief. Special thanks are given to Scott Bell and Rick Twait who participated in the field work and to Tom Hill who supplied information concerning the biological and water quality aspects of this study. Kurt Peterson prepared the illustrations; Mrs. J. Loreena Ivens edited the report and Mrs. Marilyn J. Innes prepared the camera copy.

SAMPLING EQUIPMENT AND PROCEDURES

Field work consisted of performing *in-situ* sediment oxygen demand measurements, collecting benthos samples with a 9-inch Ponar dredge, and taking sediment samples for laboratory use in determining the total solids (or water) and volatile solids content of the benthic sediments.

The SOD measurement equipment and procedures utilized for this study are adaptations and modifications of those originally developed by the Water Quality Section of the State Water Survey for use in determining the influence sediments had on the dissolved oxygen balance along the upper reaches of the Illinois Waterway (Butts, 1974). Considerable attention has been given to the study of the effects of benthic oxygen usage on overlying waters in streams and lakes in the last 10 years. Oxygen depletion due to the respiration of bottom dwelling organisms has long been recognized by limnologists and environmental engineers as being significant especially in deep lakes. Historically, though, little had been done to directly quantify oxygen uptake rates. Most quantitative and qualitative work in the past has been performed with core samples in the laboratory. In recent years, however, more emphasis is being placed on *in-situ* measurements (Lucas and Thomas, 1972; James, 1974; Sonzogni et al., 1977; Polak and Haffner, 1978; Sturtevant, 1977; Polls and Spielman, 1977; and Butts and Evans, 1978). Bowman and Delfino (1978) have compiled an excellent review of the state of the art of measuring SOD in the laboratory and in the field. These authors place SOD methodologies into five classes. One is designated as the batch system, and it is the basis around which State Water Survey equipment and operating procedures have been designed.

The so-called batch system as employed by the Water Survey entails the use of a chamber respirometer equipped with a means of internally circulating water. Its operation consists essentially of containing a known volume of water over a given bottom area using either a bell, box, or pyramidal-domed chamber and measuring the DO drop with a galvanic cell oxygen probe implanted internally. For this study, a small box type sampler, which had produced excellent results for numerous shallow streams and lakes within Illinois, was used. The detailed design of the sampler is given in figure 2.

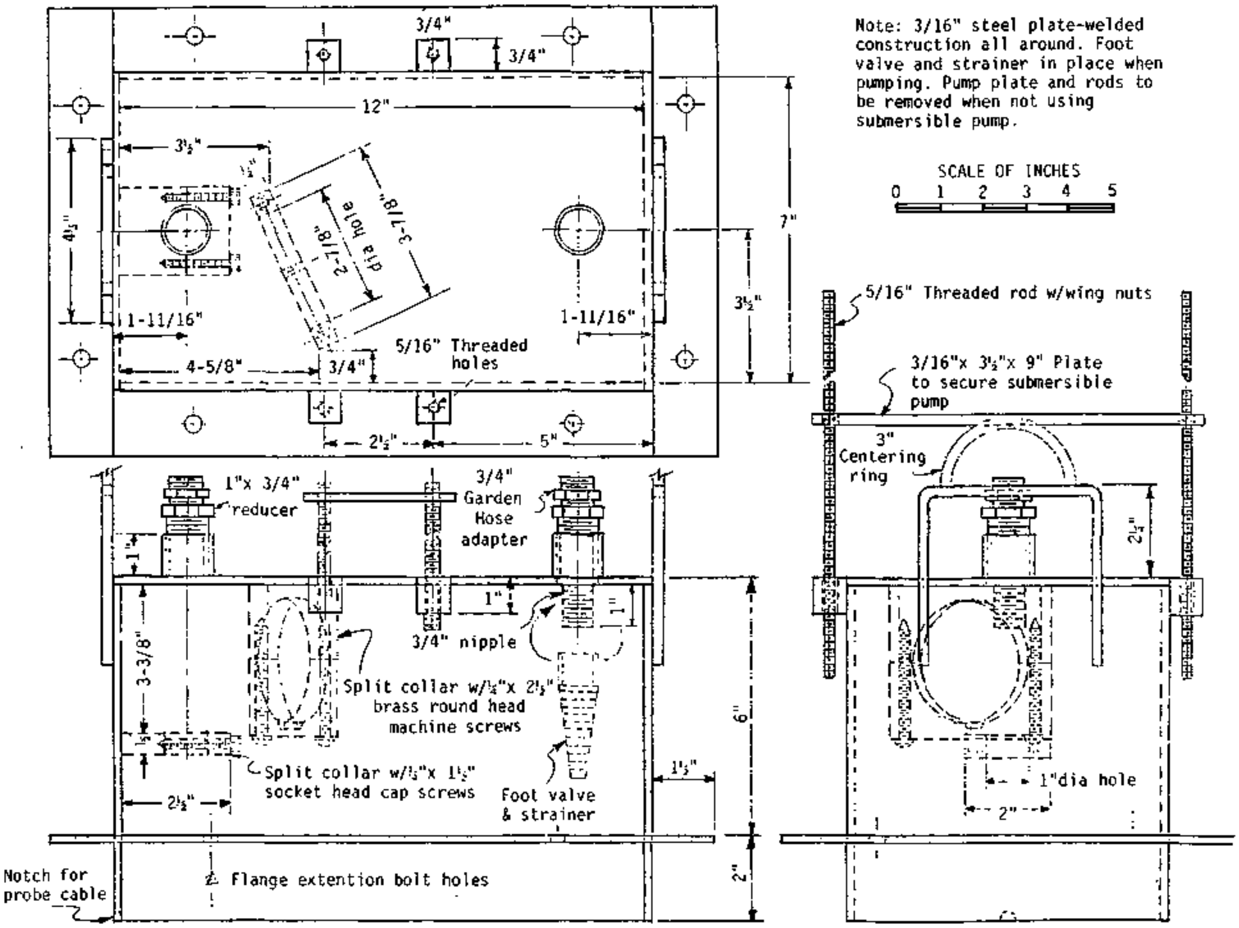

Figure 2. Portable box sediment oxygen demand sampler

The sampler is 12 inches long, 7 inches wide, and 6 inches deep to the top of the seating flange. It is fabricated of 3/16-inch steel plate welded all around. The seating flanges are 3/16-inch steel plate extending 1½ inches from the outside faces of the box sides; a 2-inch seating depth is provided. Removable water-proofed plywood extension flanges can be bolted to the steel flanges when needed.

This sampler was designed to accommodate three methods of internal water circulation or movement as depicted in figure 3. Included are two different pumping systems and an electrical stirring mechanism. The pumping can be accomplished by using either a submersible or nonsubmersible pump as diagrammatically illustrated in figures 3b and 3c. For this study, however, the stirring system shown as figure 3a was used. The stirring mechanism is attached to the large split collar welded to the inside top plate (figure 2). This collar is sized to fit a YSI 5795 submersible stirrer. The DO-temperature probe is housed within the stirrer. The stirrer operates on five size C rechargeable nickel-cadmium batteries. The power pack and recharging system are integrated directly into the design of the YSI model 57 DO meter, the instrument used by the State Water Survey in all its SOD work.

The boat used is a 14-foot flat bottom john boat having a 70-inch maximum beam and 20-inch side lengths. It is outfitted with a custom-made winch equipped with a U.S. Geological Survey "A"-reel as shown in figure 3. The winch is pivoted on a platform supported between seats. The overall design of the rig provides for its quick removal to free the boat for other uses.

Sampling is initiated by taking a Ponar dredge sample. Approximately 65 to 75 grams of the sediment obtained is scraped from the top layer. It is placed in a plastic bag which is sealed with ties and placed in a hard plastic, capped bottle. This sample is used in the laboratory for analysis of total and volatile solids.

After the relatively small sediment sample has been taken, the remaining sediments are washed through a Wildco model 190 plastic bucket equipped with a No. 30 sieve. Sieved residues are preserved in large plastic bottles with 10 percent formalin. Only one benthos sample is taken during SOD sampling runs. Time constraints and the logistics involved in a comprehensive SOD sampling program prohibit the taking of more than one benthos sample per run. From a purely scientific standpoint, this is a relatively poor sampling approach. However, for SOD work, it has proved to be satisfactory since the data are basically supportive, somewhat relative in nature, and used principally to indicate orders of magnitude of bottom degradation.

After taking the dredge sample, the boat is repositioned slightly so that the SOD readings are not influenced by the disturbed bottom area. The DO probe is calibrated at ambient water conditions by the Winkler method. The stirrer-DO probe is installed in the sampler, a battery operated recorder is hooked into the meter to provide a continuous record of the DO usage, and the sampler is lowered to the bottom after carefully expelling all trapped air. DO readings are recorded manually every 5 minutes while the temperature is recorded only at the beginning and end of a run.

DATA REDUCTION AND ANALYSES

The SOD curves as traced by the recorder (see Appendix A), were used to a great extent in analyzing and interpreting the SOD data. Interpretation of these types of curves can at times be subjective. However, knowledge of the chemical, physical, and biological conditions existing during the sampling period can greatly aid in interpreting causes and effects.

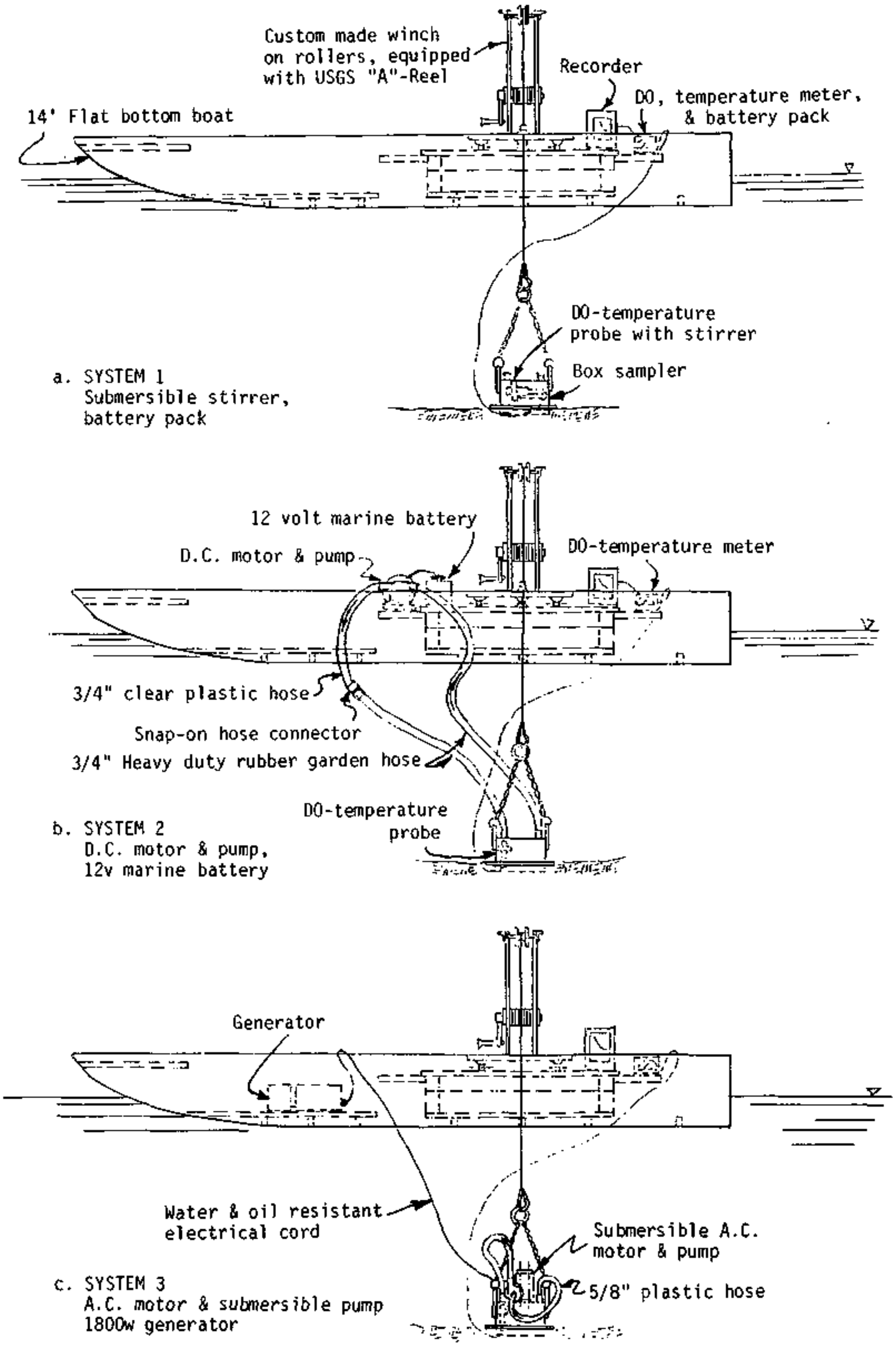

Figure 3. Portable SOD box sampler sampling systems

The SOD rates as taken from 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 applications. The general conversion formula is:

$$SOD = (1440SV)/10^3A \qquad (1)$$

where

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

The specific formula for the box sampler and stirrer combination when seated up to the flanges in sediment is:

$$SOD = 205.5\ S \qquad (2)$$

Generally, equation 2 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 disturbances 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 equation fitting techniques. Linear, exponential, and log-log fits were made and compared with the use of correlation coefficients and standard errors of estimate. The coordinate inputs of time versus oxygen uptake used to generate these curves are presented in Appendix B.

Stepwise multiple regression techniques were used to compare seven independent variables with the dependent variable, SOD. The independent parameters were: 1) water temperature, 2) dissolved oxygen of overlying water, 3) total number of macroorganisms, 4) percent dry solids, 5) percent volatile solids, 6) alkalinity, and 7) logarithms of the total number of plankton. This analysis was made to determine if relationships exist between some readily measured physical, chemical, and biological parameters and SOD. If causal relationships were found to exist, they were utilized in data interpretation relative to causes and effects.

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

$$SOD_T = SOD_{20}\ (1.047^{T-20}) \qquad (3)$$

where

SOD_T = SOD rate at any temperature, T° 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 (Butts et al., 1978).

The SODs expressed in terms of the standard areal rate units of $g/m^2/day$ can be converted to mg/1 for a given segment or reach of water by the formula:

$$G' = 3.28\ Gt/H \qquad (4)$$

where

G' = oxygen used by sediments per reach, mg/1
G = SOD, $g/m^2/day$
t = detention time per reach, days
H = average water depth in the reach, feet

This formula has been developed on the assumption that the bottom area of the water body approximates the water surface area. This is a valid assumption for Horseshoe Lake. The expression shows that the oxygen depletion in milligrams per liter per section of lake or reach of stream is directly related to the areal demand and the detention time, and inversely related to the average water depth.

RESULTS AND DISCUSSION

The overall results of the SOD study are very good and informative. The information generated provides a good base from which to evaluate the degraded conditions of the sediments and the effects of these sediments on the oxygen resources of the lake.

The term SOD, as used in the results of this report, refers to the total DO usage measured *in-situ;* it includes suspended algae respiration. Specific reference to that portion exerted by the sediments will be referred to as corrected SODs or benthal oxygen usage or demand.

The three scheduled sampling runs at stations 2, 3, 4, 7, and 8 were completed successfully. Oxygen uptake was recorded for time intervals ranging from 60 to 70 minutes. The SOD curves as traced in the field by the recorder and the manually recorded backup values are presented in Appendices A and B, respectively.

The ambient SOD rates plus those corrected to 25° C are presented in table 1. The values represent incremental linear rates; the breakpoints were approximated with the use of the traced curves in Appendix A and the data in Appendix B. The last value listed under each station represents the linearized value for the whole curve. The SOD rates considered to best represent overall conditions at the time of sampling are presented in table 2.

The physical, chemical, and biological data used in the SOD evaluation and interpretation is presented in Appendix C. The temperature is in degrees Celsius and represents the average of the beginning and ending value. The DO value is the concentration recorded in the sampler immediately at the beginning of the run. Alkalinity is expressed in terms of $CaCO_3$.

Relationships of Variables

The SOD curves in Appendix A and the reduced values presented in tables 1 and 2 indicate that the respiration rates, as measured in the box sampler, are somewhat variable throughout the lake. Also, the early and late summer rates are significantly higher than the fall rates; this is expected because differences in water temperatures between the two seasons are great.

Stepwise regression techniques were used to isolate the principal parameters causing the variability and to formulate them into an empirical but usable predictive equation. A number of water chemistry parameters could have been included in the analysis but the only one chosen was alkalinity. This choice was made on the basis that short term alkalinity fluctuations in this type of lake reflect algal activity. Algal activity in turn was suspected of influencing SOD rates both directly and indirectly. Lucas and Thomas (1972) and Butts and Evans (1978) have reported that algal respiration can influence *in-situ* SOD rates significantly in a box type sampler. The logarithms to the base 10 were used as an input for the plankton numbers because of the extreme range in values which occurred at the time of SOD sampling. Plankton counts ranged from a low of 7455/ml to a high of 100,432/ml.

Table 1. Ambient and Temperature-Corrected SOD Rates

Station	Temperature, T(° C)	Time frame (minutes)	SOD (g/m^2/day) at T° C	
				at 25° C
June 27-28, 1978				
2	31.3	0-20	5.14	3.85
		20-40	4.11	3.08
		40-65	3.29	2.46
		0-65	4.11	3.07
3	32.5	0-23	5.81	4.12
		23-63	3.85	2.73
		0-63	4.57	3.24
4	31.4	0-20	5.14	3.83
		20-45	4.11	3.06
		45-60	6.17	4.60
		0-60	4.97	3.70
7	31.0	0-15	10.96	8.32
		15-35	12.33	9.36
		35-60	8.22	6.22
		0-60	10.28	7.80
8	28.7	0-60	3.42	2.60
August 30-31, 1978				
2	22.5	0-25	4.93	5.53
		25-70	4.11	4.61
		0-70	4.40	4.94
3	25.3	0-27	3.04	3.00
		27-62	2.94	2.90
		0-62	2.98	2.94
4	24.5	0-30	4.59	4.53
		30-60	5.00	5.12
		0-60	4.79	4.90
7	23.9	0-5	0	0
		5-70	6.17	6.49
8	25.6	0-35	7.63	7.42
		35-65	6.85	6.66
		0-65	7.27	7.07
October 25-26, 1978				
2	13.9	0-7	0	0
		7-37	3.08	5.13
		37-67	2.40	4.00
		7-67	2.74	4.56
3	16.1	0-60	1.61	2.68
4	14.2	0-30	1.71	2.81
		30-60	2.06	3.38
		0-60	1.88	3.09
7	13.2	0-65	2.28	3.92
8	14.4	0-10	0	0
		10-60	2.06	3.35

The simple correlation coefficients generated between all the variables during the statistical manipulation of the data are presented as a matrix in table 3. The sample size of 15 is large enough to show some statistically significant trends and interrelationships between parameters. Plankton numbers appear to be, by far, the factor most influencing the measured SOD rates. The correlation coefficient is 0.83 which means that approximately 69 percent of the observed variation in results can be attributed to this factor. This strongly indicates that respiration of suspended algae is being

Table 2. Best Estimate of SOD Rates

Temperature	*Station*	*SOD (g/m^2/day)* 6/27-28/78	8/30-31/78	10/25-26/78
Ambient	2	3.29	4.11	2.40
	3	3.85	2.94	1.61
	4	6.17	5.00	2.06
	7	8.22	6.17	2.28
	8	3.42	6.85	2.06
25° C	2	2.46	4.61	4.00
	3 ,	2.73	2.90	2.68
	4	4.60	5.12	3.38
	7	6.22	6.49	3.92
	8	2.60	6.66	3.35

Table 3. Simple Correlation Coefficient Matrix

	Temp	*DO*	*No. of macro*	*% Solids*	*% VS*	*Alk.*	*Log no. plank.*	*SOD*
Temperature	*X*	.17	.12	.04	-.38	-.48	.60	.65
Initial DO		X	-.15	-.09	-.03	-.09	.15	.39
Number of macroorganisms			X	.59	-.38	-.34	.11	.15
% Solids				X	-.79	-.15	.09	.15
% Volatile solids					X	.38	-.54	-.48
Alkalinity						X	-.81	-.70
Log of number of plankton							X	.83
SOD								X

measured in the chamber along with true SOD. Algae production may also influence SOD rates directly in that dead cells settle to the bottom where they are subjected to bacterial decomposition and nutrient recycling.

A highly significant relationship between algal counts and alkalinity did materialize as was contemplated; the correlation coefficient was —0.81. The negative indicates that as algal production increases the total alkalinity of the water is reduced. This correlates well with normal limnological processes since photosynthetic cells abstract carbon dioxide from the bicarbonates present after using up the available supply of free carbon dioxide.

An anomaly of some degree appears to occur in the relationship between volatile solids and plankton. The benthic sediments did not exhibit an organic content proportional to the algal productivity in the overlying water. The correlation coefficient between percent volatile solids and the log of the plankton counts actually shows a significant inverse relationship. A rational explanation of this could be that bacterial recycling of the nutrients from algal fallout is very rapid in productive areas of the lake. The suspended algae and the benthic bacteria biochemical activities appear to be mutually supportive. Conceivably, benthic bacterial densities may become so great that a buildup of excessive amounts of volatile material (relative to algal production) cannot be achieved.

The correlations between temperature and SOD and temperature and plankton counts are both highly significant. As expected, the higher SOD rates and plankton counts tend to occur at the higher water temperatures. Consequently, to make comparisons between this lake and other water bodies the data must be adjusted to a standard temperature.

An interesting correlation exists between the flocculent nature of the sediments (percent solids) and the number of macroorganisms. The actual value is not particularly high; however, it is positive and significant. This indicates that the more compact sediments tend to harbor greater numbers of benthic organisms. A study of the sediment characteristics of the very watery, flocculent sediments of Lake Meredosia (Lee et al., 1975), an Illinois River backwater lake, indicated similar results; i.e., watery sediments provide poor benthos substrates. Except for possibly station 4, the sediments appear to be watery; in 10 of the 15 samples, water constituted at least two-thirds of the sample portion analyzed. Most SOD rates measured in this type of sediment can probably be attributed to a microdemand, particularly from bacteria.

The significance of analyzing the data by stepwise regression analysis is demonstrated by the results presented in table 4. The two most significant factors relative to oxygen usage in the respiration chamber are plankton numbers and initial DO concentration; approximately 76.2 percent of the total variation in oxygen uptake could be explained by using only these two variables in the regression equation. Temperature explains an additional 2.7 percent of the variation. The other four parameters, however, account for only 2.4 percent of the variation. Consequently, the oxygen usage can readily be explained using only the logarithm of the plankton counts per milliliter (cts/ml), initial DO concentration in mg/1, and the temperature in ° C. The regression equation relating these factors to oxygen uptake in the sampler is:

$$SOD = 3.39 \log P + 0.266\, DO + 0.0578\, T - 14.67 \qquad (5)$$

where

SOD = the oxygen uptake as measured in the sampler inclusive of algal respiration
P = plankton, cts/ml
DO = dissolved oxygen concentration, mg/1
T = water temperature, ° C

A stochastic formulation such as this can aid in predicting generalized conditions expected to occur when input data approximate that for which the equation was derived. For equation 5 the approximate data ranges are: P (7000-101,000), DO (6.0-13.4), and T (13.2-32.5). This equation has been used to gain some insight as to the state of degradation of the benthic sediments at stations 1,5, and 6 at which no SOD measurements were made. Plankton, DO, and temperature inputs are available from the routine water quality sampling program. The DO uptake predicted to occur for ambient conditions during the three sampling runs are presented in table 5.

The predicted oxygen usages given in table 5 do not represent strict SOD values. Suspended algae respiration is inherently included in the results because of the nature of the data used to develop the regression equation. Nevertheless, the probability is great that the sediments at stations 1 and 6 have high oxygen demand potentials. The sediments in the area of station 5 exhibit the lowest SOD potential. This is probably because station 5 is in the center of an active sand and gravel mining operation.

The degraded state of the benthic sediments can best be assessed by comparing these results with those available from previous studies made in Illinois with similar equipment and techniques. On the basis of values obtained at 90 sampling locations in northeastern Illinois streams, Butts and Evans (1978) categorized the degraded state of sediments according to the criteria outlined in table 6. However, before a direct comparison is made, the Horseshoe Lake rates need to be adjusted to some degree to account for the influence of algal respiration.

Table 4. Multiple Correlation Coefficients for Stepwise Variable Additions*

Parameter	*Multiple correlation* *Correlation*	 *Determination*	*Standard error of estimate*
Log of number of plankton	0.831	0.690	1.17
Initial DO	0.873	0.762	1.06
Temperature	0.888	0.789	1.05
% Solids	0.894	0.800	1.07
% Volatile solids	0.902	0.813	1.09
Alkalinity	0.902	0.813	1.16
Macroorganisms	0.902	0.813	1.23

* *Relative to sediment oxygen demand. SOD in g/m^2 /day*

Table 5. Estimated SOD Rates at Stations 1, 5, and 6

Station	*Plankton (cts/ml)*	*DO (mg/1)*	*Ambient T° C*	*Estimated SOD (g/m^2/day)* *at T° C*	 *at 25° C*
June 27-28, 1978					
1	22,523	15.9	31.0	6.11	4.64
5	38,483	6.0	26.0	3.97	3.79
6	47,093	11.9	29.0	6.01	5.00
August 30-31, 1978					
1	100,170	14.5	28.4	7.78	6.66
5	16,380	5.5	24.2	2.47	2.56
6	20,685	11.2	25.0	4.38	4.38
October 25-26, 1978					
1	21,158	10.4	16.2	3.70	5.54
5	7,875	7.0	13.0	1.15	2.00
6	5,933	10.3	13.8	1.66	2.78

Table 6. Generalized Benthic Sediment Conditions in Northeastern Illinois Streams as Characterized by SOD Rates

Generalized benthic sediment condition	*SOD range at 25° C (g/m^2/day)*
Clean	<0.5
Moderately clean	0.5-1.0
Slightly degraded	1.0-2.0
Moderately polluted	2.0-3.0
Polluted	3.0-5.0
Grossly polluted	5.0-10.0
Sewage sludge-like	>10.0

Note. From Butts and Evans (1978)

Adjustment for Algal Respiration

As briefly discussed earlier, suspended algae respiration contributed greatly to the field recorded oxygen uptake in the SOD chamber. This phenomenon had not been a significant factor in analyzing SOD results for other Water Survey studies. For example, algal counts occurring during SOD measurements in Lake Meredosia, a lake physically similar to Horseshoe Lake, were 2100 cells/ml or less (Lee et al., 1975). This density is small compared with the counts of up to 100,000/ml observed in Horseshoe Lake. Obviously, some adjustment had to be made to the gross SOD measurements to account for algal respiration so that a realistic benthal rate could be estimated.

Bain (1968) experimentally developed a simple formula by which algal respiration in terms of milligrams per liter per hour of DO usage is equal to the chlorophyll level in micrograms per liter times 0.001. In a literature review, Ferrara and Harleman (1978) report the ratio by weight of oxygen used during respiration to that of cell mass ranging from 0.67 to 1.19; they report a ratio of 0.81 from a field study. A literature search as a part of this study failed to reveal any reference equating respiratory oxygen use to cell counts, either of a generalized nature or for specific species.

Unfortunately, enumeration and species identification are all that were available for this study, limiting alternatives to some gross approximation. This was done by calculating the average unit differential oxygen usages per cell at 25° C and assuming these differences were due primarily to plankton densities. This assumption has some validity in that the benthos mass was relatively small at all stations during the three sampling periods (see Appendix C), and except for temperature changes, the lake was not subjected to any unusual conditions which would greatly affect bacterial densities. Temperature differentials were accounted for by adjusting all SOD rates to a base value of 25° C. The interaction between algal and bacterial populations was ignored. The resultant correction factor used is 3×10^{-5} g/m^2 /day of oxygen usage per algal cell at 25° C. The data used to derive this value are given in the last column of table 7. The extreme maximum and minimum values were eliminated and the remaining 13 were averaged to arrive at the approximate correction factor.

The adjusted SOD rates are given in table 8. They show the same variability from station to station and from sampling period to sampling period as do the unadjusted rates except the values are scaled down proportionally by the removal of the algal influence.

The lake sediments, as a whole, can be broadly classified as moderately polluted to polluted based solely on an SOD assessment. Station 3 sediments, near the industrial lagoon outfall, appear to have the lowest demand, and the sediments in the area of station 7 appear to have the highest demand. The sediment oxygen demand at station 3 possibly is being minimized by the flushing or cleansing action of the currents emanating from the lagoon outfall. A similar rationalization could be applied to the highest values observed at station 7; this station is in a dead zone of the lake having no flow-through current action, thereby creating conditions favorable for a buildup of oxygen demanding sediments. In contrast to this, station 8 is located along the main flow-through route of the lake, and SOD rates here are somewhat lower than those at all stations except station 3.

Table 9 is a tabulation of some SOD rates measured by the Water Survey at various lakes and water impoundments within the state. In comparing the Horseshoe Lake values with these, two items are worth noting and commenting upon. First, the rates of SOD for disturbed sediments for the Horseshoe Lake measurements are low compared with those of most of the other

Table 7. Data Used to Compute Unit Plankton Respiration Rates

Period *	*Plankton, P (cts/ml)*	*SOD at 25° C (g/m^2/day)*	*Period difference* * *	*Plankton difference* (ΔP)	*SOD difference* (ΔSOD)	O_2 *used/cell* $\frac{\Delta SOD}{\Delta P} \times 10^{-4}$
Station 2						
1	21,893	2.46	2-1	1,155	2.15	18.61
2	23,048	4.61	2-3	15,015	0.61	0.41
3	8,033	4.00	1-3	13,861	-1.54	-1.11
Station 3						
1	19,609	2.73	2-1	-2,809	0.17	-0.61
2	16,800	2.90	2-3	9,345	0.22	0.23
3	7,455	2.68	1-3	12,154	0.05	0.04
Station 4						
1	25,278	4.60	2-1	62,292	0.52	0.08
2	87,570	5.12	2-3	80,062	1:74	0.22
3	7,508	3.38	1-3	17,770	1.22	0.69
Station 7						
1	61,846	6.22	2-1	38,586	0.27	0.07
2	100,432	6.49	2-3	85,837	2.57	0.30
3	14,595	3.92	1-3	47,251	2.30	0.49
Station 8						
1	48,300	2.60	2-1	41,633	4.06	0.98
2	89,933	6.66	2-3	79,013	3.31	0.42
3	10,920	3.35	1-3	37,380	-0.75	-0.20

* 1 -June 27-28, 1978
2 -August 30-31, 1978
3 -October 25-26, 1978
**Period 2 minus period I, etc.

Table 8. SOD Rates Corrected for Algal Respiration

Date, 1978	*Station*	*Corrected SOD rate at 25° C (g/m^2/day)*
June 27-28	2	1.80
	3	2.14
	4	3.84
	7	4.36
	8	1.15
August 30-31	2	3.92
	3	2.40
	4	2.50
	7	3.50
	8	3.96
October 25-26	2	3.76
	3	2.46
	4	3.15
	7	3.48
	8	3.02

Table 9. SOD Rates Measured in Illinois Lakes and Impoundments

	% Solids	*% VS*	*SOD rate at 25° C ($g/m^2/day$)* *Disturbed*	 *Stabilized*
Lake DePue			4.17	2.59
Lake Meredosia Sta. 4	23.7	8.8	14.16	4.74
Lake Meredosia Sta. 5	23.7	9.8	90.99	3.85
Lake Meredosia Sta. 9	30.6	9.8	68.24	2.83
Fox Lake	37.8	9.2	5.70	3.44
Nippersink Lake	20.8	20.6	49.58	8.32
Pistakee Bay	24.7	15.3	177.06	31.57
Keokuk Pool Sta. 5	49.7	6.4	10.89	1.61
Keokuk Pool Sta. 9	53.1	4.9	9.17	2.99
Keokuk Pool Sta. 6	64.7	3.7	6.74	5.99
Horseshoe Lake Sta. 2	26.5	11.5	4.30	3.16
Horseshoe Lake Sta. 3	26.5	11.6	2.83	2.33
Horseshoe Lake Sta. 4	43.7	7.1	2.35	3.16
Horseshoe Lake Sta. 7	26.4	10.0	4.47	3.78
Horseshoe Lake Sta. 8	37.6	7.5	2.96	2.71

Note: Horseshoe Lake values are an average of three seasonal values adjusted for algal respiration

lakes or impoundments that have been sampled. Second, the SOD rates for stabilized sediments for Horseshoe Lake do not appear to be excessive and may even be on the low side of what can be expected to occur in some Illinois lakes or impoundments. The low rates of SOD for Horseshoe Lake disturbed sediments indicate that the immediate oxygen demands resulting from chemical oxidation reactions occur less readily in Horseshoe Lake benthic sediments. Chemical oxidation reactions are likely to be mediated by the by-products of the sediments under anaerobic conditions. All evidence indicates that anaerobic conditions are not a serious consideration for the shallow waters of Horseshoe Lake compared with the other bodies of water noted in table 9. Therefore the lack of chemical oxygen demand is a plausible reason for the relative low disturbed SOD rates in the lake.

Principal Causes of SOD

To aid in identifying the principal cause or causes of SOD at each station, statistical regression curve-fitting techniques were used to determine if the SOD curves best fit a linear, log-log, or semi-log model. A linear usage is indicative principally of a high bacterial demand, whereas a pronounced curvilinear usage is usually indicative of a high macro invertebrate demand (Butts and Evans, 1978; McDonnell and Hall, 1969; Edwards and Rolley, 1965; and Rolley and Owens, 1967). A nonlinear usage can also occur because of a mixed demand of bacteria, algae, and macrofauna. If the SOD is mostly the result of a macrodemand, a semi-log fit probably occurs since this demand theoretically proceeds at a rate proportional to the remaining oxygen concentration. For example, fingernail clam oxygen uptake at 100 percent DO saturation has been found to be approximately 3.8 times as great as that at 30 to 40 percent DO saturation (Butts and Sparks, 1977).

Ten of the 15 sets of data were almost perfectly linear having correlation coefficients in excess of 0.99. Four of the remaining five sets fit either a linear or log-log model equally well with correlation coefficients exceeding 0.99. Only the August data for station 4 showed a relatively poor linear fit; the linear correlation coefficient was only 0.89 versus 0.94 for a log-log fit.

This deviation from linearity at station 4 is probably not the result of macroinvertebrate respiration since their numbers were relatively low at this time. However, the algal counts were very high and this fact may have influenced the shape of the curve.

The overall results indicate that the probable cause of SOD in Horseshoe Lake is microorganisms. The maximum number of macroinvertebrates found at any station was slightly greater than 1000 organisms per square meter and these were mostly *Chironomidae* larvae. Tens of thousands of these organisms are needed to significantly influence SOD rates (Butts and Evans, 1978; Edwards and Rolley, 1965; Butts and Sparks, 1977; and Hunter et al., 1973). Hunter et al. (1973) found that tubificid worms in the Passaic River in New Jersey respire at a rate of 3.2×10^{-5} grams of O_2 per worm per day. They report other investigators have found tubificid worm respiration rates to be as low as 0.6×10^{-5} grams of O_2 per worm per day. Conservatively applying the former figure to *Chironomidae* larvae, we find that 1000 organisms would contribute only about 0.03 g/m^2 /day of SOD to the values measured in the lake. This is hardly significant and supports the hypothesis that the demand is principally micro in nature.

Predictive Model

As part of the overall limnological study of the lake, a series of dissolved oxygen measurements were made at several stations during periods other than full daylight. These measurements are considered representative of SOD and algal respiration without significant influence of photosynthetic activity. They formed a basis for testing the validity of a predictive model, herein developed, that can be useful for assessing the gross effects of SOD on the overlying water of a lake.

Casey and O'Connor (1978) have proposed that the rate of oxygen diffusion from the atmosphere into a quiescent body of water can be expressed by:

$$Q = f \quad A \quad (C_s - C) \quad t \qquad (6)$$

where

Q = quantity of oxygen absorbed in time, t
f = absorption coefficient
A = air-water interfacial area
C = dissolved oxygen concentration at saturation
C = ambient DO concentration

For a volumetric element of a lake, a simplistic model for approximating the net dissolved oxygen for a specific time period, under dark, quiescent conditions, can be derived by equations 4 and 6. The basic model can be described by:

$$DO = C - DO_{used} + \text{aeration} \qquad (7)$$

where DO_n is the net DO concentration for a column of lake water for a period of time, t. Aeration is a function of the DO deficit (C_s —C) and C, in turn, is a function of DO_{used} DO usage can result from SOD, dissolved biochemical oxygen demand (BOD), and algal respiration. For a lake, BOD can be neglected since it is normally small compared with SOD and algal respiration. SOD-algal respiration can be functionally combined and represented by G^1. A first trial DO deficit can therefore be represented by (C_s —C —G^1). Replacing the DO deficit in equation 6 with this expression and making unit conversions to provide aeration in terms of concentration yields:

$$q = (ft/h)[C_s - C - (Gt/24h)] \qquad (8)$$

where

q = DO absorbed, mg/1
h = water column depth, meters
f = absorption coefficient, m/hr
t = time, hours

Substituting equations 4 (in terms of metric units) and 8 into equation 7 provides a simple mathematical formula by which DO depletions can be estimated during 'stagnant' nocturnal conditions.

$$DO_{net} = C - (Gt/24h) + (ft/h)[C_s - C - (Gt/24h)] \qquad (9)$$

The absorption coefficient has been reported to range between 0.004 and 0.006 m/hr (Casey and O'Connor, 1978). Note that when supersaturation occurs, i.e., $C > C$, oxygen is lost to the air across the water-air interface at the same rate as oxygen would have been absorbed into the water for a similar numerical deficit. Equation 3 was incorporated into the model to compensate for temperature variation effects on oxygen usage rates, and the dissolved oxygen saturation values were computed with the formula developed by the American Society of Civil Engineers (Committee on Sanitary Engineering Research, 1960).

One set of dissolved oxygen measurements was started during late evening, night, and early morningon August 16 at shallow water stations 2, 3, 4, 6, and 7. These observations are presented in table 10 and were used to verify the predictive model. Although no *in-situ* SOD measurements were made during this period, they were made approximately 2 weeks later for stations 2, 3,4, and 7. These values were corrected for differences in plankton counts between the two periods, and the adjusted values were used as inputs to the model. Equation 5 was used to estimate the SOD factor for station 6 where no *in-situ* SOD measurement was made. The estimated oxygen usage rates are tabulated in table 11 and results of the simulations are presented in figure 4. Overall good fits were achieved between the generated curves and the observed data, with station 3 exhibiting excellent agreement and station 7 showing fair to good agreement. Consequently, equation 9 can be used confidently to assess the relative effects of benthal oxygen demand and algal respiration on the DO of the overlying water of a lake.

Table 10. Observed Nocturnal Surface Temperatures and DO Values, August 16-17, 1978

Station	*Depth (ft)*	*Time (CDT)*	*Temperature (° C)*	*DO (mg/l)*
2	2.58	2045	27.8	12.0
		0145	26.5	10.1
		0450	26.0	8.5
3	2.25	2040	28.2	8.6
		0135	27.5	7.1
		0445	27.5	6.3
4	0.83	2045	28.8	13.2
		0125	25.1	8.4
		0430	25.6	6.0
6	1.58	1930	29.0	14.0
		2345	27.0	9.7
		0235	26.0	8.4
7	1.50	1925	28.2	15.4
		2335	26.3	11.6
		0225	25.7	8.8

Table 11. Estimated Oxygen Usage Rates for August 16-17, 1978

Station	*Plankton (cts/ml)*	*DO usage, algal respiration (g/m^2 /day)*	*Sediment DO usage (table 8) (g/m^2/day)*	*Total DO usage (g/m^2 /day)*
2	36,592	1.10	*3.92*	5.02
3	25,725	0.77	2.40	3.17
4	110,775	3.31	2.50	5.81
7	100,432	3.01	3.50	6.51
6	50,610	1.52	5.04	6.56*

**Computed by equation* 5

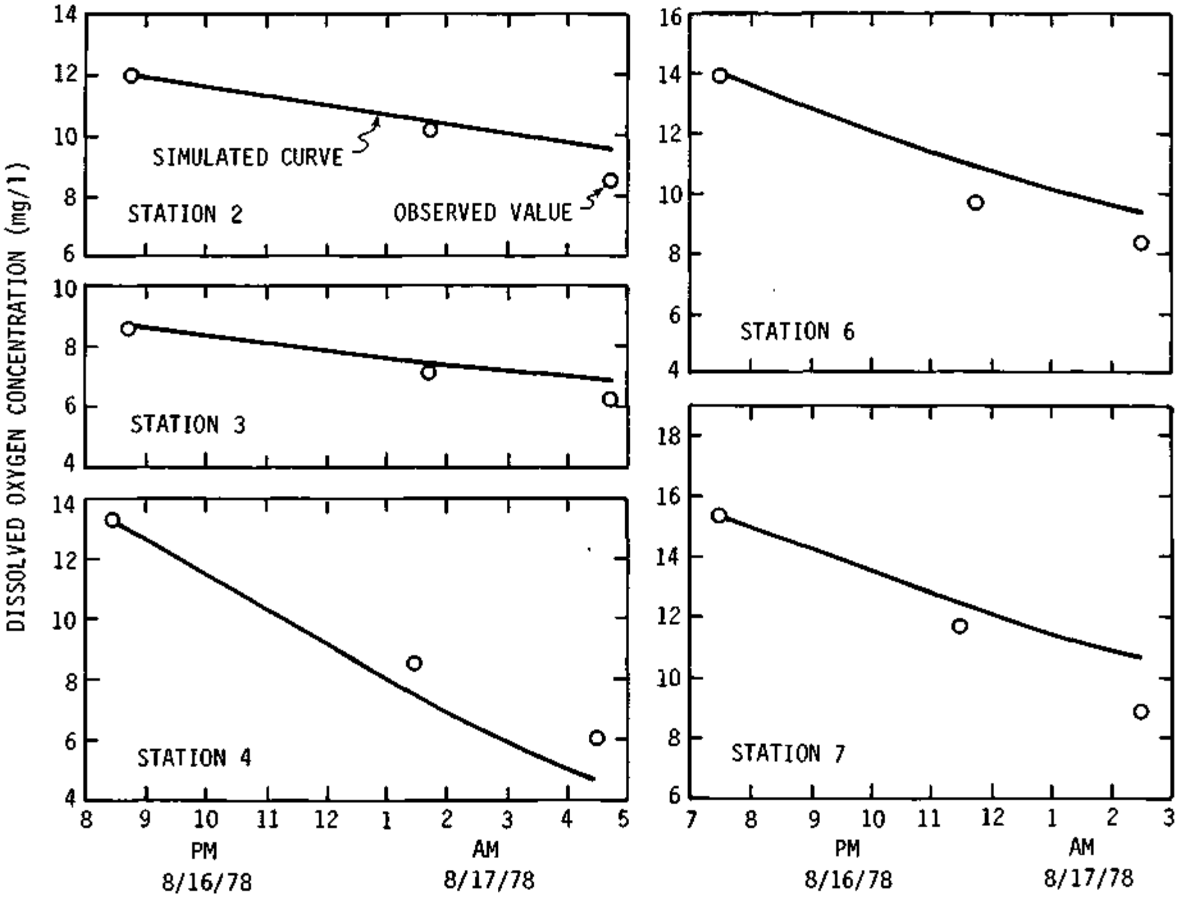

Figure 4. Simulated quiescent-nighttime dissolved oxygen curves

A somewhat hypothetical but interesting analysis can be made of DO conditions during persistent periods of heavily clouded, windless summer days. As an example, with the use of equation 9 in conjunction with the data in tables 10 and 11 and with the assumption that quiescient, dark conditions existed after August 16, only about 36 hours would be required for complete DO depletion in Horseshoe Lake. A more realistic situation could be developed for winter conditions when the lake is sealed with ice and covered with snow. Surface aeration would be totally absent, algal productivity would be very low, and water temperatures would be near 0° C. Only benthal oxygen demand would be a significant source of oxygen usage, so the appropriate usage rate should exclude algal respiration. With the use of the average of the values given in table 8 of 3.0 g/m^2 /day, corrected to a 0° C value of 1.0 g/m^2 /day, and with an average lake depth of 2 feet, total oxygen depletion would occur in less than a week if the initial DO concentration had been at saturation. Because winters are not particularly severe in this area of Illinois, this condition has not been directly observed; usually some areas of open water, particularly in the area of the steel mill lagoon outfall, exist throughout the winter. The minimum under-ice DO observed during the water quality sampling program was 5.3 mg/1.

CONCLUSIONS

The conclusions made as a result of the SOD study are:

1. *The sediments throughout Horseshoe Lake exert a significant oxygen demand on the overlying water.* Overall the sediments, based solely on SOD rates, can be classified as moderately polluted. Some areas exhibit definite signs of pollution, whereas other areas show less signs of degradation. The area of the lake receiving the discharge from the steel mill lagoons has the lowest demand, whereas dead zones of the lake exhibit the highest demands.
2. *The principal cause of the demand is bacteria and other microorganisms.* The benthic macroinvertebrate population is so small that only about 1 percent or less of the SOD can be attributed to them.
3. *The oxygen demand of the disturbed sediments is low compared to that of other Illinois lakes and impoundments studied in recent years.* The sediments, however, are easily disturbed, somewhat flocculent, and contain significant amounts of organic material. This indicates that most of the *in-situ* SOD is biological or biochemical in nature and is not due to inorganic chemical reactions.
4. *The primary productivity of the lake is very high and algal fallout may be a significant contributor to SOD.* The benthic organics needed to sustain a high bacterial SOD may come more from internally generated algal cells than from external sources of organic pollutants. Consequently, the SOD rates may be more influenced by external sources of dissolved nutrients needed to sustain algal blooms than by direct input of organic laden particulate matter.
5. *The dissolved oxygen in the lake is rapidly depleted in the absence of surface aeration or photosynthetic oxygen production.* A simple mathematical model was developed and verified to predict dissolved oxygen concentrations for warm, quiescent, 'black box' conditions. The model indicates that only about 36 hours would be needed to completely deplete DO under these conditions. Less than a week would be needed to totally deplete the DO if the lake were completely sealed by ice and snow during the winter.

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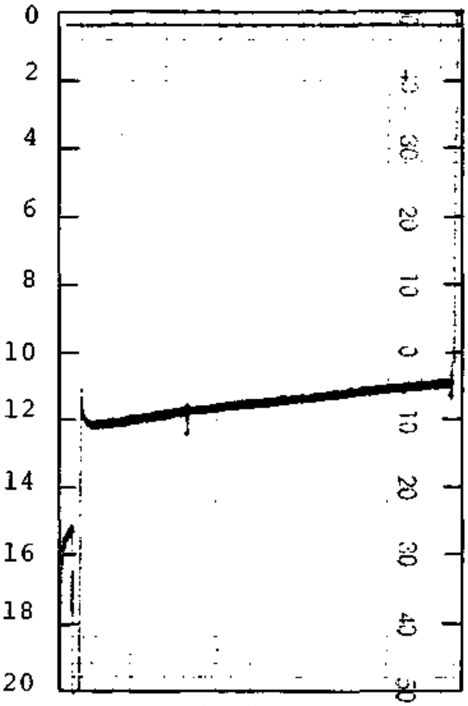
APPENDIX A

Field-Traced Sediment Oxygen Demand Curves

X axis = time in minutes, 7.5 min/unit; Y axis = DO remaining in mg/l



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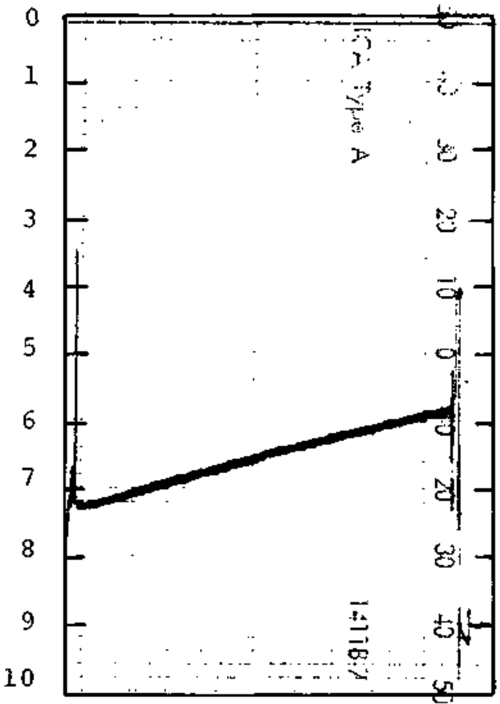

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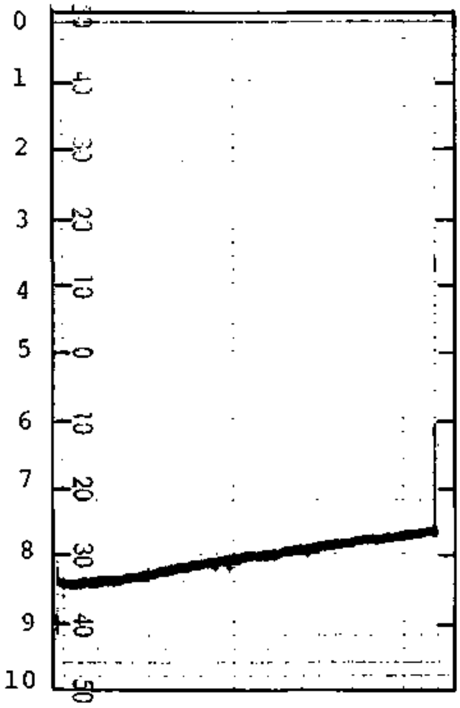

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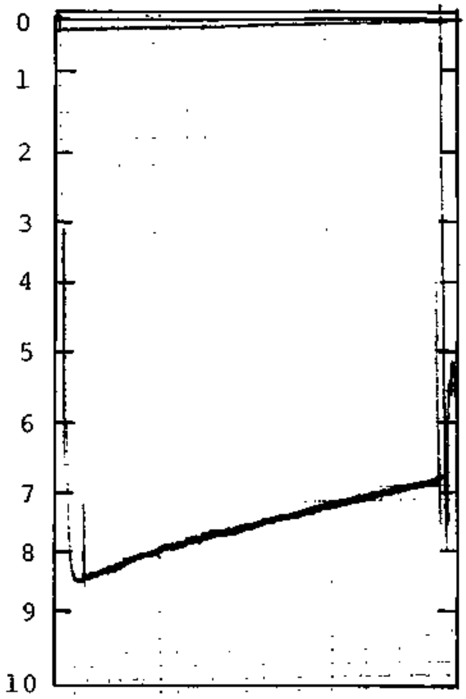
Station 2

APPENDIX A. Continued

X axis = time in minutes, 7.5 min/unit; Y axis = DO remaining in mg/l



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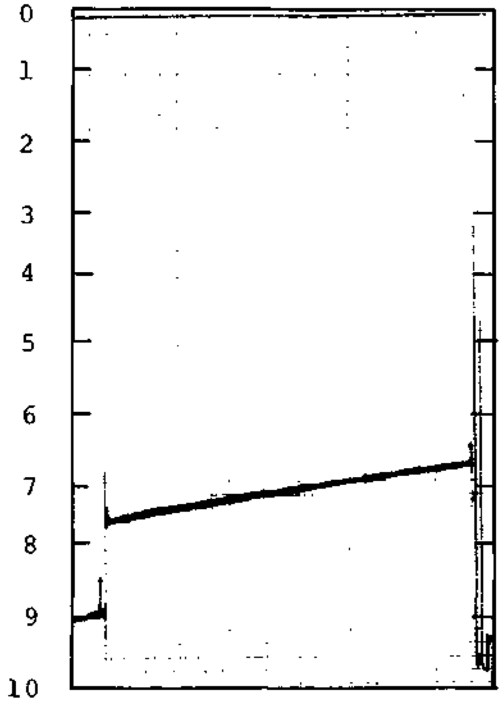

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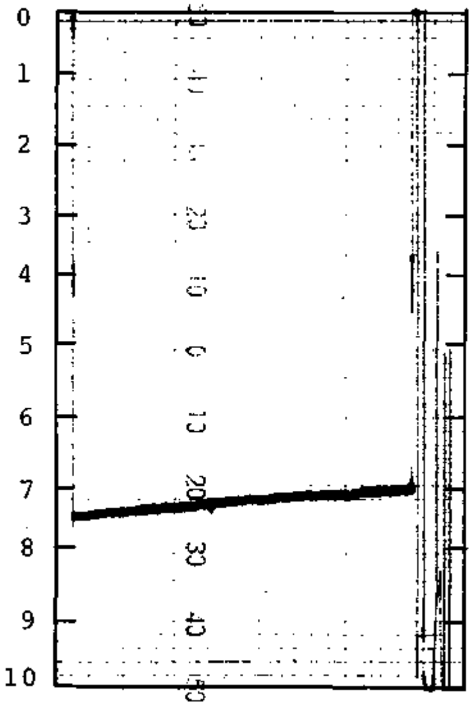

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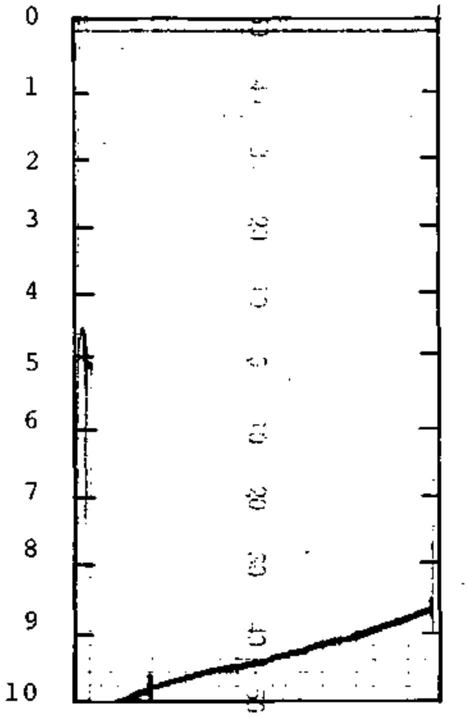
Station 3

APPENDIX A. Continued

X axis = time in minutes, 7.5 min/unit; Y axis = DO remaining in mg/l



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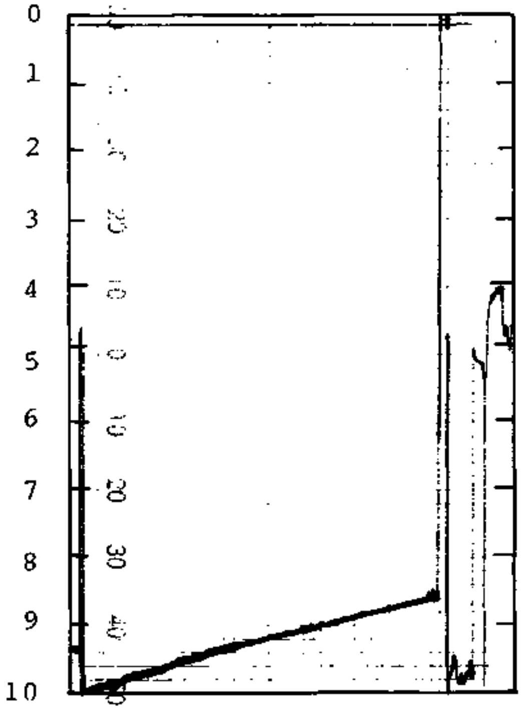

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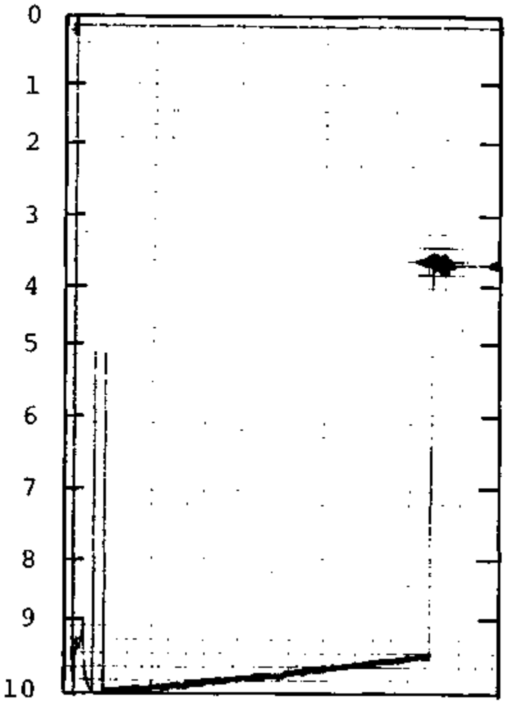

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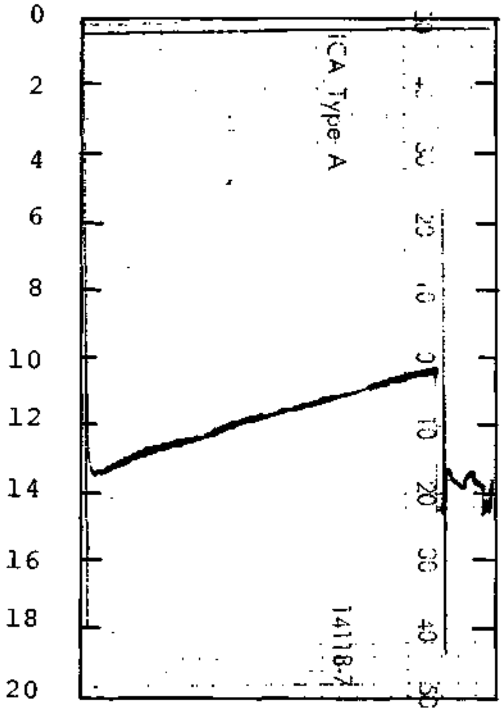
Station 4

APPENDIX A. Continued

X axis = time in minutes, 7.5 min/unit; Y axis = DO remaining in mg/l



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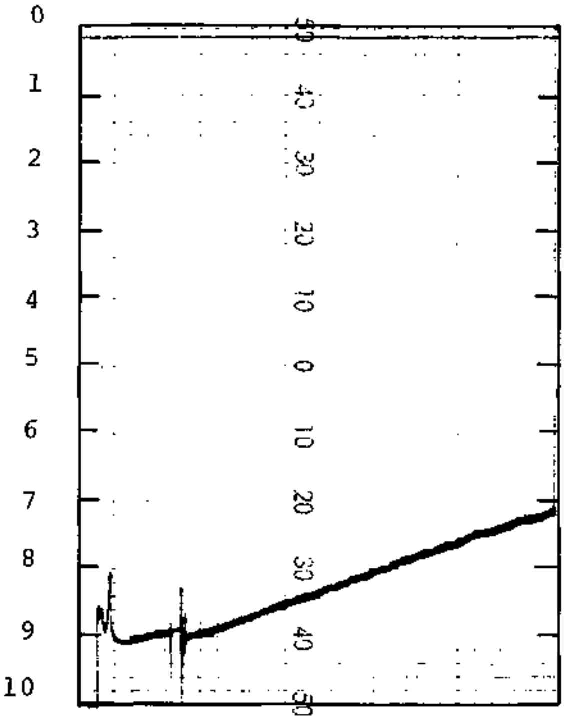

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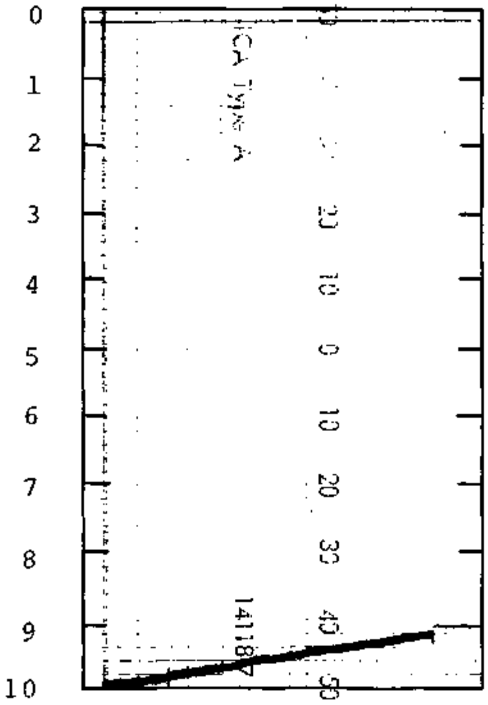

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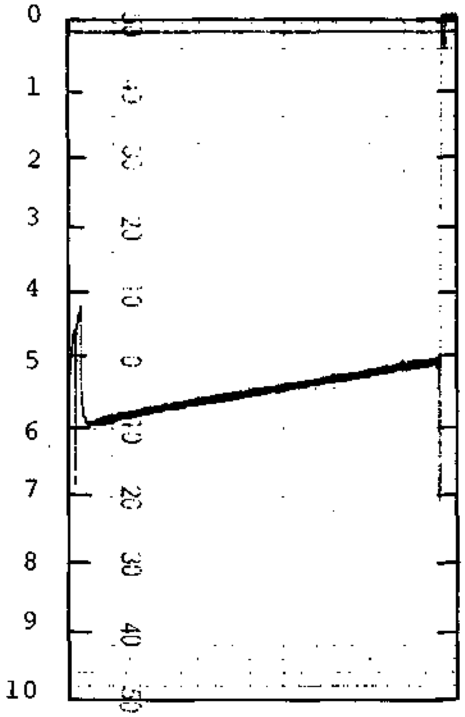
Station 7

APPENDIX A. Concluded

X axis = time in minutes, 7.5 min/unit; Y axis = DO remaining in mg/l



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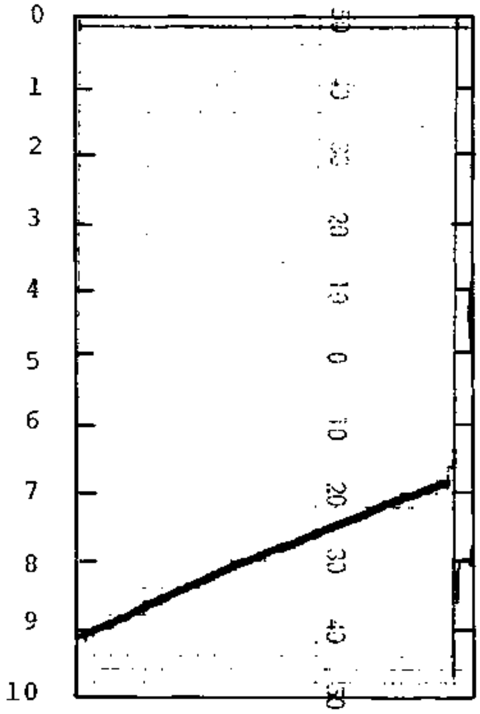

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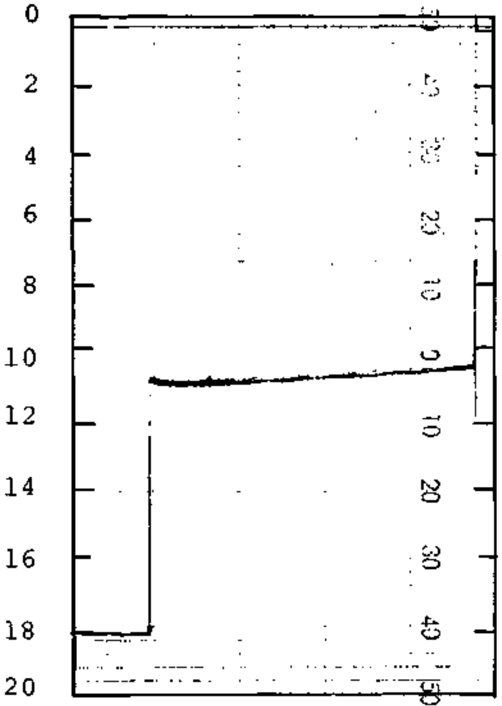

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Station 8

APPENDIX B

Field-Recorded DO Usage, Horseshoe Lake

DO-used versus elapsed time from recorded field notes
(∑T in minutes; ∑DO in mg/l)

Station 2		*Station 3*		*Station 4*		*Station 7*		*Station 8*	
∑T	*∑DO*	*∑T*	*∑DO*	*∑T*	*∑DO*	*∑T*	*∑DO*	*∑T*	*∑DO*
				June 27-28, 1978					
0	0	0	0	0	0	0	0	0	0
5	0.10	3	0.05	5	0.20	5	0.30	5	0.10
10	0.20	8	0.20	10	0.30	15	0.80	10	0.20
15	0.25	13	0.30	15	0.40	20	1.10	15	0.30
20	0.50	18	0.50	20	0.50	25	1.40	20	0.35
25	0.60	23	0.65	25	0.60	30	1.70	25	0.45
30	0.70	28	0.70	30	0.70	35	2.00	30	0.50
35	0.75	33	0.80	35	0.80	40	2.20	35	0.60
40	0.90	38	0.90	40	0.90	45	2.40	40	0.70
45	1.00	43	1.00	45	1.00	50	2.60	45	0.75
50	1.05	48	1.10	50	1.15	55	2.80	50	0.80
55	1.10	53	1.20	55	1.30	60	3.00	55	0.90
60	1.20	58	1.30	60	1.45			60	1.00
65	1.30	63	1.40						
Temperature, °C									
Begin 32.1		33.0		31.2		33.2		28.1	
End 30.5		32.0		31.5		30.8		29.3	
				August 3-31, 1978					
0	0	0	0	0	0	0	0	0	0
5	0.05	2	0.10	5	0.15	5	0	5	0.10
10	0.15	7	0.15	10	0.30	10	0.05	10	0.30
15	0.30	12	0.22	15	0.40	15	0.20	15	0.50
20	0.45	17	0.27	20	0.50	20	0.40	20	0.70
25	0.60	22	0.35	25	0.60	25	0.60	25	0.90
30	0.70	27	0.40	30	0.67	30	0.75	30	1.10
35	0.80	32	0.45	35	0.72	35	0.95	35	1.30
40	0.95	37	0.50	40	0.80	40	1.10	40	1.50
45	1.05	42	0.62	45	1.05	45	1.20	45	1.70
50	1.15	47	0.70	50	1.20	50	1.40	50	1.85
55	1.25	52	0.75	55	1.30	55	1.55	55	2.00
60	1.37	57	0.82	60	1.40	60	1.70	60	2.15
65	1.45	62	0.90			65	1.85	65	2.30
70	1.50					70	1.95		
Temperature ° C									
Begin 22.2		25.4		24.5		23.3		25.4	
End 22.8		25.1		24.5		24.4		25.7	

APPENDIX B. Concluded

DO-used versus elapsed time from recorded field notes
(∑T in minutes; ∑DO in mg/l)

Station 2		*Station 3*		*Station 4*		*Station 7*		*Station 8*	
∑*T*	∑*DO*	∑*T*	∑*DO*	∑*T*	∑*DO*	∑*T*	∑*DO*	∑*T*	∑*DO*
October 25-26, 1978									
0	0	0	0	0	0	0	0	0	0
7	0	5	0.05	5	0.05	5	0	3	0
12	0.05	10	0.10	10	0.07	10	0.10	5	0
17	0.10	15	0.12	15	0.15	15	0.15	10	0
22	0.20	20	0.15	20	0.20	20	0.20	15	0.05
27	0.25	25	0.20	25	0.22	25	0.25	20	0.10
32	0.35	30	0.25	30	0.25	30	0.35	25	0.15
37	0.45	35.	0.30	35	0.30	35	0.40	30	0.20
42	0.50	40	0.35	40	0.35	40	0.45	35	0.25
47	0.55	45	0.37	45	0.40	45	0.50	40	0.32
52	0.60	50	0.40	50	0.45	50	0.55	45	0.40
57	0.65	55	0.42	55	0.50	55	0.60	50	0.40
62	0.75	60	0.47	60	0.55	60	0.67	55	0.45
67	0.80					65	0.72	60	0.50
Temperature °C									
Begin 13.8		16.2		14.2		13.2		14.2	
End 13.9		16.0		14.2		13.2		14.6	

APPENDIX C

Stepwise Regression Analysis Data Input

Parameter	*6/27-28/78*	*8/30-31/78*	*10/25-26/78*
Station 2			
Temperature, ° C	31.3	22.5	13.9
Initial DO, mg/1	12.3	7.2	8.4
Macroorganisms, no./m^2	364	420	1148
Percent solids	21.0	25.5	33.1
Percent VS	11.4	10.1	12.9
Alkalinity, mg/1 as CaCO$_3$	84.9	49.2	105.6
Plankton, cts/ml	21,893	23,048	8,033
SOD, g/m^2/day	3.29	4.11	2.40
Station 3			
Temperature	32.5	25.3	16.1
Initial DO	8.4	7.6	7.5
Macroorganisms	211	77	153
Percent solids	23.3	27.2	29.1
Percent VS	11.1	10.3	13.3
Alkalinity	130.0	147.2	125.1
Plankton	19,609	16,800	7,455
SOD	3.85	2.94	1.61
Station 4			
Temperature	31.4	24.5	14.2
Initial DO	10.1	10.0	10.0
Macroorganisms	1072	382	192
Percent solids	59.5	40.0	31.7
Percent VS	4.2	7.2	10.0
Alkalinity	67.3	82.0	174.3
Plankton	25,278	87,570	7,508
SOD	6.17	5.00	2.06
Station 7			
Temperature	31.0	23.9	13.2
Initial DO	13.4	9.05	10.0
Macroorganisms	498	382	440
Percent solids	24.2	26.8	28.1
Percent VS	10.3	9.4	10.4
Alkalinity	52.4	50.6	102.5
Plankton	61,846	100,432	14,595
SOD	8.22	6.17	2.28
Station 8			
Temperature	28.7	25.6	14.4
Initial DO	6.0	9.1	10.4
Macroorganisms	1167	382	345
Percent solids	39.7	34.9	38.2
Percent VS	6.8	7.2	8.4
Alkalinity	67.9	60.5	174.3
Plankton	48,300	89,933	10,920
SOD	3.42	6.85	2.06