Ohio Sea Grant

EVALUATION OF SEDIMENT OXYGEN DEMAND (SOD) MEASUREMENTS IN LAKE ERIE

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Ohio Sea Grant Program

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I would like to express my gratitude to the crew of the R/V Hydra, whose rigorous efforts in collecting and analyzing the samples made this study possible. I am pleased that we are able to produce copies of this research effort and make it available to other scientists.

Charles E. Herdendorf
Director
Lake Erie Programs

INTRODUCTION

Background and Objectives

As a result of the Water Quality Act of 1965 (P.L. 89-234), the amendments of the Federal Water Pollution Control Act of 1972 (P.L. 92-500) and the Great Lakes Water Quality Agreement (U.S. Department of State 1972), as well as various other regulatory measures from state and local government agencies, a renewed interest in the dissolved oxygen balance of natural waters has developed. Of particular concern has been the depletion of oxygen in the central basin hypolimnion of Lake Erie, which has become anoxic several times since 1929 (Charlton 1979; Dobson and Gilbertson 1971; Fish et al. 1960; Kleveno et al. 1971; Thomas 1963). The lack of hypolimnetic oxygen in Lake Erie can cause serious fish kills and destruction of bottom fauna, as well as other ill effects (Beeton 1963; Britt 1955; Burns and Ross 1972b; Carr and Hiltunen 1965). The significance of sediment oxygen demand in Lake Erie was introduced upon publication of "Project Hypo" (Burns and Ross 1972a) in which Lucas and Thomas (1971) and Burns and Ross (1972c) reported that the depletion of dissolved oxygen in the hypolimnion of the central basin was predominantly due to the oxygen consumption associated with the sediments rather than the biochemical or chemical oxygen demand of the overlying water.

The two major components of the hypolimnetic oxygen depletion in Lake Erie are the water column oxygen demand (WOD) and the sediment oxygen demand (SOD). The WOD represents the biological, biochemical, and chemical oxygen demands in the water column with the demand primarily due to algal and bacterial respiration. Sediment oxygen demand is a term used to describe the utilization of dissolved oxygen (DO) from the overlying and interstitial water of the sediments by various processes which include biological and chemical oxygen demands. The biological demand consists of the respiration from algae, bacteria and macroinvertebrates while the chemical demand is from the oxygen consumed during the oxidation of inorganic chemical species. The primary factor contributing to the SOD in Lake Erie is believed to be the deposition of autochthonous organic matter, predominantly algal cells, which accumulate on the lake bottom and either undergo decomposition or respiration (Burns 1976; Burns and Ross 1972c; Herdendorf 1980; Lucas and Thomas 1971). Burns and Ross (1972c) found that bacterial decomposition of the sedimented algal cells accounted for approximately 88 percent of the hypolimnetic oxygen uptake in the central basin during the summer of 1970. Actual historic values of SOD rates for Lake Erie vary from 0 to 3.90 g $O_2 m^{-2}$ day^{-1} (Blanton and Winklhofer 1971; Burns and Rosa 1980; Lasenby 1979; Lucas and Thomas 1971; Snodgrass and Fay 1980). A discussion of these values will appear later in this paper when factors influencing SOD rates such as methodology, time of year sampled and ambient water quality parameters have been reviewed.

The overall objective of this study was to describe that portion of hypolimnetic oxygen loss associated with sediment processes in Lake Erie. The specific objectives of the study are to:

1. define the effects of SOD rates on the hypolimnetic oxygen concentrations of Lake Erie;
2. analyze the relationship of the variables involved in this process to formulate a practical and predictive mathematical model;
3. determine if SOD rates can be used as a direct indicator of the trophic level of Lake Erie and the limitations of such a use; and
4. evaluate the methodology that has been applied towards the SOD determination of Lake Erie for applicability in other bodies of water.

Site Description

The Lake Erie basin is separated into three distinct bathymetric regions -- the western basin which is generally less than 11 m in depth, the central basin with depths of slightly more than 25 m and the eastern basin whose deepest portions reach 64 m (Figures 1 and 2). The average surface areas for the western, central and eastern basins are 3,276 km^2, 16,177 km^2 and 6,238 km^2, respectively (Verber 1950). Aside from bathymetric and areal differences, the basins also have their own sedimentary or hydraulic zones reflecting the mean grain size of the sediments. Mean grain size distribution can be used to estimate the degree of mixing of the sediments and its relation to the depositional energy (Thomas et al. 1976).

The western basin region contains predominantly fine-grained sediments as can be seen by comparing Figures 3a, 3b and 3c. Because of the shallow-water conditions and more sediment input than output to the western basin, an unstable sediment budget is created thus causing constant resuspension and redeposition of sediments (Thomas et al. 1976). However, in the central basin they showed a west to east trend in grain-size increase (Figure 3d) which is caused by the prevailing westerly and southwesterly winds. These winds increase the fetch of the basin, thus creating relatively stable sediments. The deep-water eastern basin shows a further increase of mean grain size (Figure 3d) with increasing depth reflecting a decrease in energy or increase in stability. Another important aspect to consider is the stratification of the basins. Due to its shallowness and constant mixing, the western basin does not stratify and thereby a decrease of oxygen due to SOD will not have as great an effect as if the basin could stratify. However, both the central and eastern basins are deep enough to be completely stratified during the summer, which leads to a problem of hypolimnetic oxygen depletion.

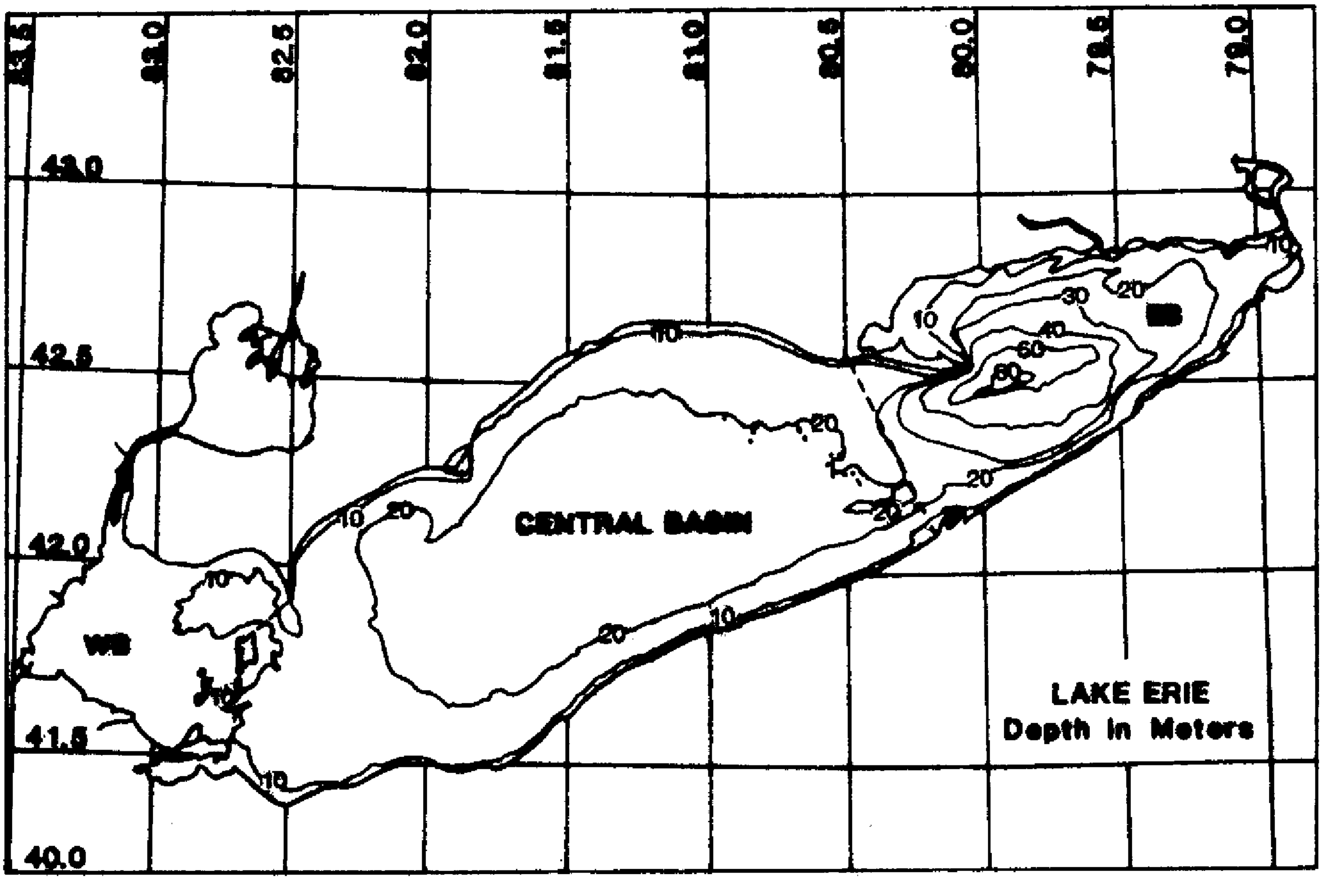

Figure 1. Lake Erie Bathymetry

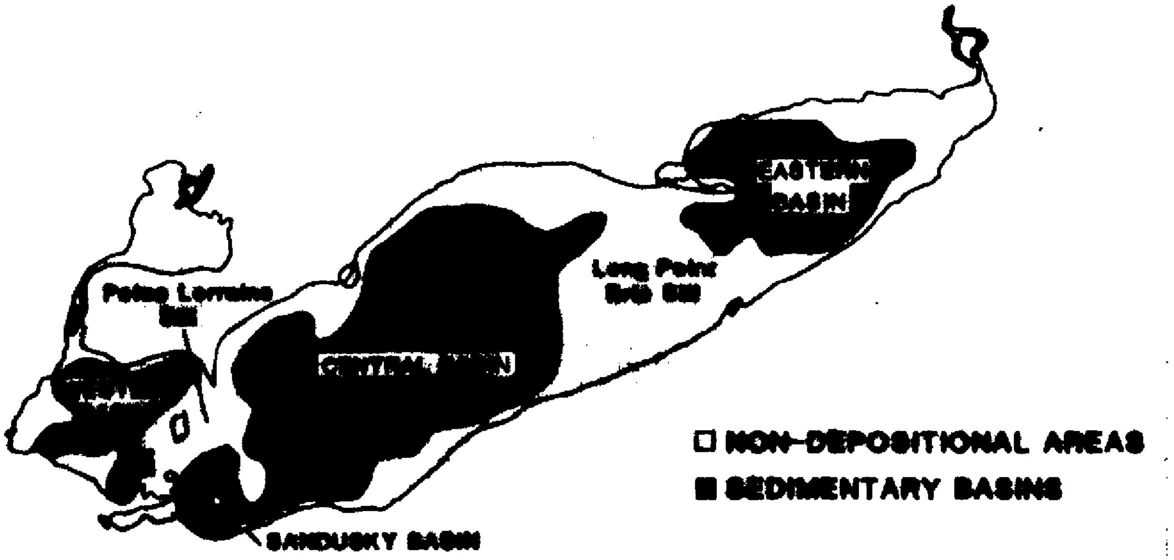

Figure 2. Lake Erie Sedimentary Basins

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Figure 3a. Distribution of Percent Sand-size Fraction in the Surficial Sediment of Lake Erie.

Figure 3b. Distribution of Percent Silt-Size Fraction in the Surficial Sediment of Lake Erie.

Figure 3. Grain-Size Characteristics of Surficial Sediment of Lake Erie (Thomas et al. 1976).

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Figure 3d. Distribution of Mean Grain-Size Diameter of the Surficial Sediments of Lake Erie.

Grain-Size Characteristics of Surficial Sediment of Lake Erie (Thomas et al. 1976).

Study Plan

Experiments were conducted during the summers of 1978 and 1979 to determine the rates and relative significance of the SOD and the WOD. The sampling strategy for 1978 was to obtain a spatial distribution of SOD rates. In 1978, the SOD and several other parameters (Table 1) were measured at 28 stations throughout the lake (Figure 4; Table 2). All stations were sampled during the period from 27 July to 22 August (Julian dates 208-234) in which the majority of the lake was stratified. During the stratified period all the stations sampled had a minimum DO concentration of at least 3.8 mg $0_2/1$.

The sampling strategy for 1979 was to measure any changes in the WOD and SOD rates that may occur throughout the summer stratification or as a result of the fall overturn. In 1979 the WOD and SOD rates and related parameters (Table 1) were measured at two central basin stations (Figure 5; Table 2) which were representative of the area that commonly becomes anoxic. Several measurements were taken in four cruises during June (15-21), July (18-23) and August (16-22) in which the lake was thermally stratified, and at the end of September (29-Oct. 2) during the fall overturn. The Julian dates for the four cruises were 166-172, 199-203, 228-234 and 272-275, respectively.

TABLE 1

LIST OF VARIABLES USED (1978-1979)

1978		1979	
Variable	Units	Variable	Units
Water		Water	
Day	Gregorian or Julian	Day	Gregorian or Julian
Sample Time	Hours, minutes	Sample Time	Hours, minutes
DO	mg O_2 l^{-1}	WOD Rate	g O_2 $m^{-3}d^{-1}$
Temperature	^oC	DO	mg O_2l^{-1}
Depth	meters	Temperature	^oC
Hypolimnion	meters (thickness)	Depth	meters
Stratification	yes or no	Hypolimnion	meters (thickness)
Total P	ppb	Stratification	yes or no
Surface Light	microeinsteins ($m^{-2}sec^{-1}$)	TS-Suspended	mg l^{-1}
		TS-Residual	mg l^{-1}
Sediment		TS-Volatile	mg l^{-1}
		pH	S.U.
SOD Rate	gO_2 $m^{-2}d^{-1}$	Conductivity	umhos cm^{-1}
Sediment Light	percent surface light	Alkalinity	mg l^{-1} as $CaCO_3$
Total Mn	ug/g dry wt.	Chlorophyll a	ug l^{-1}
Total P	ug/g dry wt.	Pheophytin	ug l^{-1}
Total Fe	ug/kg dry wt.	NO_2+NO_3-N	ug l^{-1}
TVS	percent dry wt.	NH_3-N	ug l^{-1}
TS	percent dry wt.	Heterotrophic Bacteria	cells/100 ml sample
Total Benthos	m^2 or $(23\ cm)^2$		
Oligochaetes	m^2 or $(23\ cm)^2$		
Diptera	m^2 or $(23\ cm)^2$	Sediment	
Amphipoda	m^2 or $(23\ cm)^2$		
Heterotrophic Bacteria	cells/15 g sediment	SOD Rate	g $O_2m^{-2}d^{-1}$
		Heterotrophic Bacteria	cells/15 g sediment

TABLE 2

STATION LOCATIONS FOR SOD STUDY

Station	Basin	Latitude	Longitude
1978			
10	E	42°40'48"	79°41'30"
11	E	42°48'12"	79°33'30"
14	E	42°32'18"	79°37'00"
15	E	42°38'30"	79°56'00"
18	E	42°25'18"	80°04'48"
24	C	42°05'54"	80°29'00"
26	C	42°24'00"	80°38'12"
28	C	42°35'30"	81°01'00"
30	C	42°25'48"	81°12'18"
32	C	42°04'54"	81°00'42"
35	C	41°45'48"	81°23'00"
42	C	41°57'54"	82°02'30"
45	C	41°36'24"	81°53'48"
48	C	42°02'48"	82°21'54"
50	C	41°48'48"	82°30'06"
52	C	41°31'54"	82°27'12"
57	W	41°49'54"	83°01'06"
60	W	41°53'30"	83°11'48"
62	E	42°51'00"	79°54'00"
64	E	42°12'00"	80°03'00"
66	W	41°58'00"	82°40'00"
68	W	41°45'00"	82°51'00"
70	W	41°46'00"	83°20'00"
73	C	41°58'40"	81°45'25"
76	W	41°36'30"	83°04'00"
78	C	42°07'00"	81°15'00"
79	C	42°15'00"	80°48'00"
80	E	42°42'42"	80°14'54"
81	W	41°39'30"	82°50'40"
82	C	41°34'30"	82°10'00"
83	C	41°42'30"	82°19'10"
N	C	41°53'00"	81°27'00"
R	C	42°10'00"	81°37'00"
1979			
A1	C	41°50'42"	81°51'00"
A2	C	42°06'30"	80°37'29"

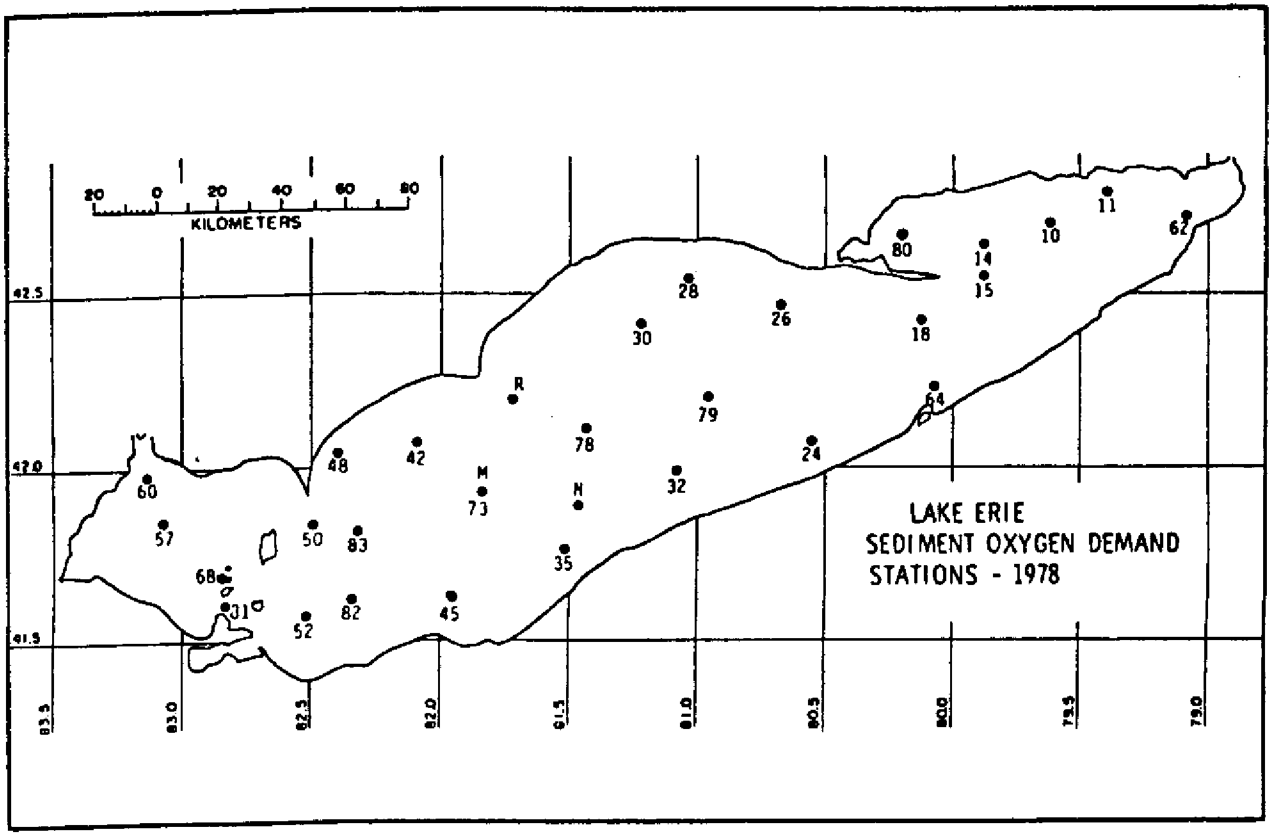


Figure 4. Sampling stations for 1978 SOD cruise.

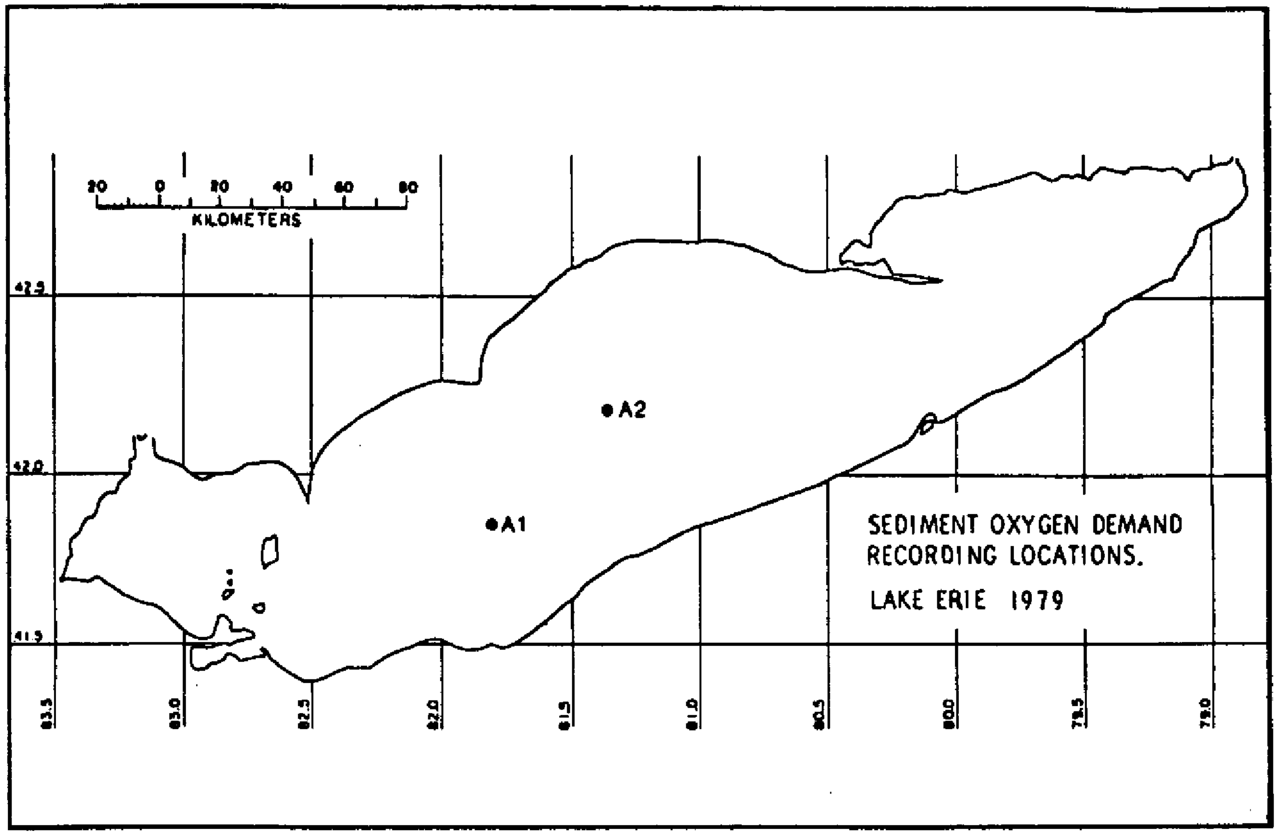


Figure 5. Sampling stations for 1979 SOD cruises.

LITERATURE REVIEW

Introduction

The two major causes of oxygen depletion in aquatic systems are the WOD and the SOD. The significance of the oxygen demand from water, particularly through the assimilation of organic wastes, has been well documented (Hanes and Irvine 1966; Owens 1964; Owens et al. 1972; Polak and Haffner 1978; Snodgrass and Holloran 1977). Even though the need to account for the oxygen consumption by the sediments has been established (Edwards and Rolley 1965; Golterman 1967; Mathis and Butts 1981; Owens and Edwards 1963), the SOD has generally been overlooked in water quality studies.

Alsterberg (1972) showed that decomposition of organic matter in the sediments can severely deplete the oxygen content of the overlying water. The problem of oxygen consumption by organic benthic deposits had also been recognized by Streeter and Phelps (1925), Mortimer (1941, 1942) and Jansa and Ackerlindh (1941). Streeter (1931), when referring to a study on the Illinois River, pointed out that about 40 percent of the total oxygen demand of the river was exerted by organic benthic deposits. Baity (1938) studied the oxygen consumption of presieved and natural sediments at several depths and temperatures and established a general relationship between the thickness of the sediment layer and oxygen demand at 22°C:

$$Y = 2700X^{0.485}$$

where X is the thickness of the sediment layer (cm) and

Y is the rate of oxygen demand (mg/m^2/day of sediment surface).

Fair et al. (1941) investigated the oxygen consumption at several depths and temperatures. They also demonstrated that as the flow of water over the sediments was varied, significant differences in the dissolved oxygen content of the overlying water occurred. In studying deposits 1.5 to 10.2 cm thick, they found a higher oxygen demand from the deeper deposits; however, it was felt that this factor of depth could best be expressed as the areal concentration of organic matter as shown below:

$$Y_o = 2.45\ m^{0.485}$$

where Y_o is the initial rate of oxygen demand (g/m^2/day) and

m is the areal concentration of the organic matter in the deposit (kg/m^2).

These studies were the initial research efforts concerning the science of oxygen consumption by the sediments. A review of some of the factors which affect the sediment oxygen demand as well as methods used to measure the oxygen uptake rate will follow.

Sediment Thickness

The matter of sediment thickness and its effect on the oxygen demand of the sediment has been well researched. Oldaker et al. (1968) found that only the top 15 cm of the sediment affected the areal SOD. Lardieri (1954) studied paper waste sludge and noted that the fresh deposits exhibited the identical slow oxygen uptake rate as the older deposits did, presumably due to the acidic nature of the sludge. Davison and Hanes (1968) and NCASI (1971) found that fresh cellulosic deposits have a significantly higher demand than that of older deposits, and, once those deposits were consolidated, Hanes found the demand to be independent of the sludge thickness due to a decrease in oxidation of the buried sediment. Hanes suggests that one reason for possible dependency upon the sludge thickness is due to disturbance of those deposits. As the sediments become resuspended the surface area of sediment available for oxidation is greatly increased, therefore the potential oxygen demand of deeper deposits upon resuspension is quite significant (Rybak 1969). Mohlman et al. (1931) had concluded that the thickness of the sediment layer itself under quiescent conditions was not an important factor and this conclusion has been well supported (Edwards and Rolley 1965; Fillos and Molof 1972; Martin and Bella 1971; McDonnel and Hall 1969; McKeown et al. 1968; Pamatmat 1973; Stein and Dennison 1967).

Organic Content

One would also expect the amount of organic matter in the sediments to be a controlling factor of SOD; however, some studies have found this not to be the case. Anderson (1939), working with marine sediments, found the organic content of those sediments to be unrelated to the oxygen uptake as did Edwards and Rolley (1965) and Mathis and Butts (1981) with freshwater sediments. However, at low concentrations the SOD rate may become a function of the organic content. Studying sediments with 57 percent to 66 percent organic content, Belanger (1981) found no statistically significant correlation between the SOD and percent volatile solids. However, the narrow range in which the independent variable was sampled may prevent an appropriate indication of its relationship with the SOD. Hargrave (1969) found no correlation of carbohydrates, total organic matter or protein content with the SOD, but Liu (1973) showed a nonlinear correlation of SOD with the carbohydrate content above 4 cm and linear below 4 cm of sediment depth. This suggests that the carbohydrate content may be rate-limiting at lower depths possibly due to excessive amounts of carbohydrates in the top few centimeters. The lack of correlation of SOD with total organic matter is possibly due to the biodegradability of that organic matter. Only the most readily oxidized substances will promote oxygen depletion by bacteria (Walker and Snodgrass 1978), so the biodegradability of the organic matter should be more influential than the quantity of the organic matter.

Flow Rate

In the study by Fair et al. (1941) the significance of the flow rate of water over the sediments became apparent. There is no question that the SOD rate increases with resuspension of the sediments (Baumgartner and Palotas 1970; Berg 1970; Boynton et al. 1981; Butts and Evans 1979; Edwards and Rolley 1965; Hargrave 1969; Hunding 1979; Isaac 1962; Liu 1973; Pamatmat 1973; Reynolds et al 1973; Teal and Kanwisher 1961). The degree of mixing of the overlying water and the extent to which it affects the SOD rate may be quite significant. Marked increases in the SOD rate were noted when the overlying water was gently stirred without resuspending the sediments (Belanger 1981; Boynton et al. 1981; Cary 1967; Crook and Bella 1970; Graneli 1972; Graneli 1979a; Hargrave 1969; Knowles et al. 1962; Lasenby 1975; Lasenby 1979; NCASI 1978; Pamatmat 1971b; Rybak 1966), but other investigators found that there was no increase in oxygen demand with stirring until there was sufficient agitation to disturb the sediments (Davies 1975; Edwards and Rolley 1965; Hall et al. 1979; Hargrave 1969; Hargrave 1972a; Whittemore, personal communication), completely resuspend the sediments (Reynolds et al 1973) or until the sediments had been resuspended for several hours (Rybak 1969).

The National Council of the Paper Industry for Air and Stream Improvement (NCASI 1978), in a comprehensive study on the effects of interfacial velocity on SOD, concludes that the actual physical resuspension of the sediments is not the cause of the increased SOD. Rather, the increased flow caused a greater transport of soluble organic material through the boundary layer creating a rise in the SOD by making available greater amounts of substrate of oxidation. They also acknowledged the possibility of bioturbation in the sediment as another mechanism for greater transport of materials and subsequently higher SOD rates. Boynton et al. (1981) also reported the increase in the chemical oxygen demand (COD) without physical resuspension of the sediments due to the greater diffusion of the dissolved substances to the sediments with increasing velocity. Upon resuspension of the sediments the COD increased sharply, but so did the biological demand. Boynton et al. (1981) then concluded that "circulation rates for in-situ chambers should not be designed simply to maintain minimal stirring" below the velocity needed for resuspension, but should be able to reproduce as nearly as possible the natural velocities of the study area. This cannot be emphasized enough.

The consequences of intermittent or no stirring on the SOD rates is discussed by Rybak (1969), Teal and Kanwisher (1961) and Graneli (1972), who indicate that if there is no mixing of the water, an oxygen gradient develops creating an anaerobic microzone above the sediments of several centimeters. This prevents significant contact of DO with the sediments which may artificially lower the results obtained when measuring the SOD rates (Brundin 1951; Milbrink 1969; Rybak 1966). Obviously, mixing of the overlying water is needed to stimulate natural environmental conditions, but this is not easily accomplished. In an attempt to avoid this problem, Martin and Bella (1971) had simulated the amount of suspended solids in the natural environment in their experiments, implying that the suspended solids reflect the amount of disturbance of the sediments caused by the water movement of the overlying water. Other researchers have simply designed their chamber velocities to simulate those found in the study area.

Invertebrate Activity

The possibility of bioturbation in the sediment as another mechanism for greater transport of dissolved substances to be oxidized, which ultimately increases the SOD rate, has been explored by only a limited number of researchers. Using lithium chloride (LiCl) to study chemical diffusion rates into the sediments, Edwards and Rolley (1965) found a greater diffusion rate of LiCl with larger numbers of *Chironomus* sp. They also noted that the SOD rate of their mud cores did not increase proportionally with the quantity or biomass of the *Chironomus*. They felt the higher SOD rates were most likely due to the tunnels created by the larvae which produced a greater surface of sediment for oxidation and therefore increased the SOD rate. Hargrave (1970) noted a non-linear increase of oxygen consumption occurs when adding populations of the amphipod *Hyallela azteca* to sediment cores, also due to the effect of bioturbation. Graneli (1979a) also conducted experiments on the effects of *Chironomus* larvae on the SOD rate, noting that following stirring of the water, a decrease in the SOD rate was quite distinct for samples with one or no larvae while the samples containing five and three larvae showed a much smaller difference. This could partially explain the sustained oxygen demand reported by Lasenby (1979) and Whittemore (personal communication) upon stopping the mixing of the overlying water after a specified time, since the biological activity of the larvae keeps the oxygenated water in contact with the reduced or decomposing organic matter.

Since SOD rates are measured in units of oxygen consumed by a surface area of sediment over a given period of time, it may be of interest to know how much additional sediment surface is made available by the benthos. Due to benthic macroinvertebrate activity Teal and Kanwisher (1961) and Graneli (1979a) showed increases in the sediment surface area by 22 percent and 50 percent, respectively. Therefore, aside from the increase in oxygen consumption due to benthic respiration, the physical presence of the benthos may have been directly responsible for a 22 to 50 percent increase in the ambient SOD rates due to bioturbation.

Walker and Snodgrass (1978) best summarize the effects of invertebrate activity on the SOD with the following conclusions:

1. active macroinvertebrates increase the surface area of the mud-water interface;
2. they increase resuspension of the sediments;
3. they recycle organics to the mud-water interface; and
4. they increase the depth of the aerobic zone which results in increasing oxygen transfer and sediment organic decomposition.

Oxygen Concentration

Macroinvertebrate respiration and activity can be affected by the oxygen concentration of the overlying water. Davisen (1931) concluded that tubificid respiration was oxygen dependent below a critical point and observed that as the dissolved oxygen concentration was lowered in the water, the rate of glycogen consumption in Tubifex increased. This indicates that as the worms deplete the oxygen content of the water their aerobic respiration gradually switches to fermentation requiring consistently lesser amounts of oxygen. This view was also supported by Berg and Jonasson (1965) who noted that profundal species have a lower oxygen consumption when the water has a lower oxygen content and can survive for long periods during anoxia (Berg et al. 1962; Berg and Ocklemann 1959). Furthermore, Ewer (1942) and Walsh (1948) found that with large benthic populations the SOD rate is dependent upon the oxygen concentration of the overlying water. Knowles et al. (1962) further defined this dependence by observing that the sediments which contained a large number of benthic invertebrates also exhibited by a break point near 2 to 4 mg $O_2 l^{-1}$ in the SOD curve. Above 2 to 4 mg $O_2 l^{-1}$ the oxygen concentration appears to have little or no effect on the SOD rate, but below that level a strong relationship is evident.

The extent and range of dependency of the SOD rate on the oxygen concentration in the overlying water has not been established. Some investigators feel that the relationship is one of independence in the range of 2 to 8 mg $O_2 l^{-1}$ (Baity 1938; Fillos and Molof 1972; Gardner and Lee 1965; Knowles et al. 1962; Martin and Bella 1971; Mortimer 1941; Pamatmat and Banse 1969) while others note a dependency of the SOD rate on the overlying water oxygen concentration below 6 to 8 mg $O_2 l^{-1}$ (Edberg 1976; Edwards and Rolley 1965; Graneli 1977; Graneli 1978; Hargrave 1969; Hargrave 1972a; Howeler 1972; Newrkla and Gunatilaka 1982; Owens et al. 1963; Pamatmat 1973; Polak and Haffner 1978). At low oxygen concentrations (below 2 to 3 mg $O_2 l^{-1}$) a strong dependency is evident (Baity 1938; Fair et al. 1941; Martin and Bella 1971; Pamatmat 1971a; Walker and Snodgrass 1978) allowing one to conclude that diffusion of oxidizable materials to the sediment surface through the boundary layer and benthic respiration are the rate-limiting steps at the low oxygen concentrations.

The general linear relationship between the SOD rate and DO is in the normal regression formula of $y = mx+b$ (Polak and Haffner 1978) and a curvilinear relationship of oxygen concentration to SOD rate can best be expressed by the equation used by Edwards and Rolley (1965) and Owens et al. (1969):

$$Y = aC^b$$

where Y is the oxygen demand ($gO_2/m^2/hr$) and

C is the oxygen concentration in the water (Mg O_2/l) and

a and b are empirical constants

SOD Fractionation

In an attempt to define the oxygen dependency even further, many investigators have partitioned the SOD into biological and chemical components (Boynton et al. 1981; Bradley and James 1968; Dale 1978; Edberg 1976; Graneli 1977; Hargrave 1969; Hayes and MacAuley 1959; Martin and Bella 1971; Neame 1975; Pamatmat 1971a; Reynolds et al. 1973; Smith et al. 1972; Teal and Kanwisher 1961; Walker and Snodgrass 1978; Wang 1980). Walker and Snodgrass (1978) and Wang (1980) found that the biological demand occurs predominantly under aerobic conditions (greater than 2 mg/l) while the chemical fraction of the SOD generally proceeds with an inverse relationship to the dissolved oxygen concentration. In other words, the biological and chemical demands are rate limited by the availability of oxygen and the fraction of the demand under low oxygen concentrations is increasingly chemical.

The biological sediment oxygen demand (BSOD) consists of the respiration of macro- and micro-organisms. Macro-respiration is due primarily to benthic macroinvertebrates, and in some cases can be significantly affected by the algal macrophytes (Edwards 1962). Phytoplankton and bacteria contribute to the majority of the microrespiration (Butts and Evans 1978; Lucas and Thomas 1971; Neame 1975). Bacterial respiration is directly related to the amount of organic matter present through organic decomposition. The chemical sediment oxygen demand (CSOD) results from the oxidation of inorganic chemical species, particularly when approaching anaerobic conditions (Brockett and Orchard 1975). To illustrate the presence of these oxygen demands, investigators have employed bacterial and biological inhibitors to stop respiration, so the oxygen consumed is considered the CSOD. A list of these investigators and the inhibitors they used appear in Table 3.

TABLE 3

LIST OF SOME SEDIMENT OXYGEN DEMAND FRACTIONATION EXPERIMENTS

Investigator	Biological Inhibitor
Barcelona and Wang (1982)	1% phenol, 3 mM zinc acetate, 1% phenol/3mM zinc acetate
Belanger (1981)	5% formalin final solution
Berg (1970)	30g/l NaCl
Bradley and James (1968)	$HgCl_2$
Brewer et al. (1977)	0.5M and 1M phenol, 0.5M and 1M KCN
Cviic (1953)	Penicillin and Streptomycin*
Dale (1978)	1.3% formalin final solution
Dye (1983)	5% formalin
Edberg (1976)	$HgCl_2$
Graneli (1977)	0.1% $HgCl_2$, 1.5% formalin, radiation
Hargrave (1969)	10% buffered formalin
Hargrave (1972a)	1% buffered formalin
Hargrave (1972b)	2% buffered formalin
Hargrave (1978)	1% formalin final solution
Hunding (1979)	40 mg/l $HgCl_2$ final concentration
Liu (1973)	10^{-5}M to 0.5M KCN
Martin and Bella (1971)	$HgCl_2$
Pamatmat (1971a)	2.5%, 5% formalin
Pamatmat (1971b)	5% formalin
Pamatmat (1973)	5% formalin
Smith et al. (1972,1973)	formalin,50mg/l Streptomycin-SO_4*
Smith et al. (1976)	formalin
Smith et al. (1978)	3%, 5% buffered formalin
Teal and Kanwisher (1961)	formalin
Walker and Snodgrass (1978)	KCN, streptomycin-penicillin*
Wang (1980)	1% buffered formalin, 0.5-1M phenol, 10^{-5} to 0.5m KCn, 30 g/l NaCl, $HgCl_2$
Zobell and Brown (1944)	0.5% Chloroform, 0.25% formaldehyde

*Specific Bacterial Inhibitor

To prevent bacterial activity in sea water samples, ZoBell and Brown (1944) concluded that chloroform was sufficient. Another investigation in the marine environment showed that the combined effect of penicillin and streptomycin was 97 percent effective as a bactericide while penicillin or streptomycin alone was only 70 and 75 percent effective, respectively (Cviic 1953). These experiments showed that the inhibitors prevented bacterial growth, not that the inhibitors killed all bacteria present. The plate counts cannot detect living, non-reproductive cells. Certain precautions should be taken if a Winkler determination is to be made on water samples. As Marshall and Orr (1958) note, the reaction of penicillin with the iodine that is liberated in the Winkler method prevents the use of the antibiotic in such circumstances. A similar disturbance in the endpoint of the iodometric titration in the Winkler method occurs with the use of formalin as a biological inhibitor (Graneli 1977).

Wang (1980) compared four inhibitors over varied time periods for overall efficiency and effectiveness. The inhibitors tested were streptomycin-penicillin (33 mg to 33,000 units per 100 ml of sediment mixture), formaldehyde (1 percent final mixture), phenol (16 g per 300 ml of sediment mixture) and sodium chloride (15 to 20 g per 300 ml of sediment mixture). Wang also found phenol and formaldehyde to be most effective in stopping all microbial respiration immediately upon addition, with the effect lasting up to 70 hours. Due to lesser amounts of phenol needed than formaldehyde, phenol was the recommended toxicant, Graneli (1977) recommended the use of mercuric chloride when the Winkler method is employed.

Upon addition of a 2 percent formaldehyde solution, Hargrave (1972a) reported 80 percent of the oxygen consumption of the top 5 mm of the sample had ceased, but below 2 cm the formalin had no effect. This was presumably due to the predominance of the sediment chemical oxygen demand. Teal and Kanwisher (1961) observed up to a 30 percent reduction in oxygen uptake using formalin; however, Brewer et al. (1977), Dye (1983), and Edberg (1976) found little effect of their inhibitors implying the majority of their demand is chemical. Newrkla (1982) reported an unexplicable increase in the SOD rates after treatments of the sediment cores with bactericides and formaldehyde. It should be noted that whether the demand is chemical or biological depends upon the physical, biological and chemical composition of the particular sediments studied, not upon some general empirical formula for SOD that is applied to any situation.

From the observations of Pamatmat (1971a) and Walker and Snodgrass (1978) the biological demand is a function of the oxygen concentration below 1-2 mgO_2/l and is close to zero order above 1-2 mgO_2/l. The chemical demand can be either first order (Walker and Snodgrass 1978) or second order (Pamatmat 1971a) with respect to the oxygen concentration. Under low oxygen concentrations the demand is predominantly chemical depending upon the mass transfer of oxygen through the sediment layer, and dependent on the diffusivity and the depth to which the oxygen is present (Wang 1980).

Temperature

A more definitive factor of the SOD rate is the effect of temperature. Many investigators prefer to estimate SOD rates at a reference temperature for easier fit into a mathematical model. This relationship is so expressed by the following equation used by Butts and Evans (1978):

$$SOD_T = SOD_{20} 0^{T-20}$$

where SOD_T is the SOD rate at any temperature, T^oC;

SOD_{20} is the SOD rate at 20^oC; and

0 is the temperature coefficient.

There have been many values for 0 ranging from 1.040 to 1.088 (Butts and Evans 1978; Edberg and Hofsten 1973; Edwards and Rolley 1965; Karlgren 1968; McDonnell and Hall 1969; Mathis and Butts 1981; Pamatmat 1971a; Thomann 1972). At the present, a value of 1.047 is widely accepted, chosen from the Arrhenius model which is used to estimate the carbonaceous biochemical oxygen demand at various temperatures in water quality models (Butts et al. 1973). However, Mathis and Butts (1981) and Walker and Snodgrass (1978) recommended a value of 1.085 to account for sediment nitrification.

Methodology

Sediment Cores. Laboratory methods generally require the collection of "undisturbed" sediment cores (Belanger 1979; Bradley and James 1968; Davies 1975; Edberg 1976; Edberg and Hofsten 1973; Graneli 1977, 1978, 1979a, 1979b; Hargrave 1969, 1972a, 1972b; Inniss and Young 1977; Lasenby 1975, 1979; Newrkla 1982; Pamatmat 1971a, 1971b; Rolley and Owens 1967; Rybak 1966; Walker and Snodgrass 1978). The sediment cores are sealed in the laboratory and adjusted to a known thickness of sediment and a known volume of overlying water. With the cores sealed, no oxygen can enter into contact with the sediments aside from the dissolved oxygen already present in the water; thus the dissolved oxygen will be utilized by sediment and water processes. The sealed cores prevent atmospheric oxygen from entering the system. To correct for any significant oxygen consumption by the water (WOD), light and dark bottle measurements should be run for at least the duration of the experiment and incubated *in-situ* for the ambient temperature and light exposure (Belanger 1979; Davis et al. 1981; Lasenby 1979). The Winkler titration method, Warburg-type respirometers or electrolytic respirometers have also been used to measure the amount of DO consumed in the sediment cores (Bowman and Delfino 1980; Young and Baumann 1972). Knowing the surface area of sediment involved and the volume of water, the resultant drop in DO with time can be used to calculate the SOD and WOD rates.

Sediment Grabs. Laboratory SOD measurements have also been made by obtaining portions of sediment from dredge samples, usually by scraping off the top few centimeters, and adding a known mass of sediments to a BOD bottle (Barcelona and Wang 1982; Bowman and Delfino 1980; Brewer et al. 1977; Connell et al. 1982; Gardner and Lee 1965; Leutheuser 1981; Plumb and Lee 1983; Roseboom et al. 1979; Wang 1980, 1981). This procedure is quite similar to the light-dark bottle determinations (Belanger 1979) but the duration of incubation is limited due to the greater oxygen uptake caused by addition of the exposed sediments. To correct for the oxygen uptake by the water a control set utilizing water from near the sediment interface should be run.

Flow-through Techniques. These batch systems cannot be used for long-term experiments because the oxygen within the system is readily depleted. To avoid this problem, open-ended mechanisms which have a continuous flow of well-oxygenated water through them are used. The difference in the DO concentrations between the influent and effluent water along a known surface area of sediment is used to calculate the SOD rate (Belanger 1981; Fair et al. 1941; Fillos and Molof 1972; Jeppesen 1982; McKeown et al. 1968; Mueller and Su 1972; Ogunrumbi and Dobbins 1970; Oldaker et al. 1968).

Criticism of Laboratory Techniques. There have been some severe criticisms of the two laboratory methods (cores and light-dark bottles) mentioned. Even though these laboratory methods have dominated the SOD research, the major criticism is the inability to satisfactorily simulate the natural condition of the body of water sampled (Butts and Evans 1978; Hargrave and Connolly 1978; Polak and Haffner 1978; Sonzogni et al. 1977;

Sturtevant 1977) although some authors have found no difference between the laboratory and in-situ SOD rate measurements (Newrkla and Gunatilaka 1982). As a result, these laboratory determinations may misrepresent the actual SOD rate, primarily due to the disturbance of the sediment structure upon sampling and manipulation in the laboratory (Bradley and James 1968; James 1974; Reynolds et al. 1973). In particular, the "sediment BOD" experiments should not be considered an attempt to measure the actual SOD, but rather as an indication of the potential SOD under scouring velocities. Favorable considerations of the mud core respirometer technique are the selectivity of the variables which can be used in the laboratory and the relative ease of manipulation and adjustment of these variables (Bowman and Delfino 1980).

Field (In-situ) Measurements. The in-situ SOD measurement commonly uses a batch system similar to the laboratory mud-core batch system. An open-bottom chamber is lowered on top of the sediments to seal in a known surface area of sediment and a known volume of water. The oxygen within the chamber is usually monitored with the use of an electronic oxygen probe. The water should be circulated within the chamber in order to simulate natural conditions and to supply a constant diffusion potential across the probe's tip (Reynolds 1969). To supply this constant flow of water (0.3 to 0.6 m/sec; Reynolds 1969) either an internally-housed stirring mechanism can be used (Butts and Evans 1978, 1979; Butts and Sparks 1977) or a submersible pump attached to the outside of the chamber allowing the water to circulate within the chamber via plastic, tygon or rubber tubing (Butts 1974; Hall et al. 1979; Lucas and Thomas 1971; Polls and Spielman 1977). As the chamber sits on top of the sediments, the ensuing decrease in dissolved oxygen of the water, as with the laboratory technique, is predominantly due to oxygen consuming processes in the sediments. Again, a correction for the WOD can be applied using a light-dark bottle technique.

Carbon dioxide producton can also be used for SOD estimates due to respiration as described by Fontvieille and Renaud (1982). Some authors not mentioned in the text who use an *in-situ* technique include Hansmann et al. (1971); Hinga (1974); Mathis and Butts (1981); O'Connell and Thomas (1965); Pamatmat and Fenton (1968); Shapiro and Zur (1981); Smith (1973a, 1973b, 1974, 1978); Smith et al. (1973, 1974, 1976, 1979); Snodgrass (1976); and Thomas and O'Connell (1966).

The *in-situ* chambers used have been constructed from a variety of materials, such as plexiglass (Lucas and Thomas 1971) and steel (Butts 1974; Butts and Evans 1978, 1979; Butts and Sparks 1977; Butts et al 1975; Polls and Spielman 1977). Volumes of some chambers have ranged from 0.1 l (Pamatmat and Bahgwat 1973) to 500 l (Sonzogin et al. 1977), using hemispherical (Snodgrass 1976), triangular (Lucas and Thomas 1971), rectangular (James 1974) and square configurations (Butts and Evans 1979).

Continuous-Flow Measurements. Continuous flow systems are also used *in-situ* but to a much lesser degree. The common method of measurement is done by placing a semi-circular device over the sediments oriented in the direction of the current flow. The DO is measured at the influent and the effluent of the device and difference between the two measurements, along with the surface area of sediment enclosed and the flow rate of the water, is used to calculate the SOD rate (Bradely and James 1968; James 1974; McKeown et al. 1968).

Criticism of In-Situ Technique. Criticisms of the *in-situ* technique consist of lack of adequate reproductibility due to the numerous variables encountered in the field (NCASI 1979) as well as the disturbance created when the chamber is placed upon the sediments. Placement can create artificially high initial SOD rates due to resuspension

(Butts and Evans 1978; James 1974). The in-situ batch system is oxygen limited and therefore the length of time the oxygen uptake can be monitored is a function of the oxygen depletion rate itself. This may be remedied by either using the continuous flow system or by using an electrolytic respirometer to monitor the DO concentration instead of using the electronic oxygen probe. The Warburg-type electrolytic respirometer utilizes a manometric electrolysis reaction which continuously replaces oxygen consumed by the sediments (Bowman and Delfino 1980; Young and Baumann 1972). The respirometer is essential when the lower limit of DO is encountered in heavily polluted streams, low flow periods and stratified lakes. To derive an SOD rate there must be a sufficient drop (2-3 mg/l) in DO to have a significance in the calculations. When low DO concentrations were encountered, Butts and Evans (1978, 1979), Butts and Sparks (1977) and Polls and Spielman (1977) used a circulating pump on the boat's deck to enter well-oxygenated water into the chamber and then proceeded to measure the resulting SOD rates similar to the technique employed by Hunter et al. (1973). Hall et al. (1979) used a flow-through benthic chamber which at the end of an experiment could flush and exchange the water inside the chamber with the water outside without removing the instrument.

Newrkla and Gunatilaka emphasize the importance of knowing the "theoretical" SOD capacity under well-oxygenated conditions and the "actual" SOD rate under varied ambient oxygen conditions. The question then arises at low DO levels as to whether the oxygen consumption from the reoxygenated overlying waters is a potential SOD or the true SOD. Actually, the oxygen consumed by the sediments when the oxygen availability is not a limiting factor is either termed the sediment oxygen uptake or the SOD. However, under low DO concentrations which limits the oxygen consumption by the sediments, perhaps the proper term to use is sediment oxygen uptake rather than SOD. In other words, the phrases "sediment oxygen uptake" and "sediment oxygen demand" may be used interchangeably to express the oxygen depletion by the sediments under well-oxygenated conditions (above 3-4 mg O_2/l); but when the DO concentration drops to a limiting concentration (below 2-4 mg O_2/l), the oxygen utilization measured should be termed the sediment oxygen uptake instead of the SOD. The actual oxygen demand is unknown since the oxygen concentration is limited.

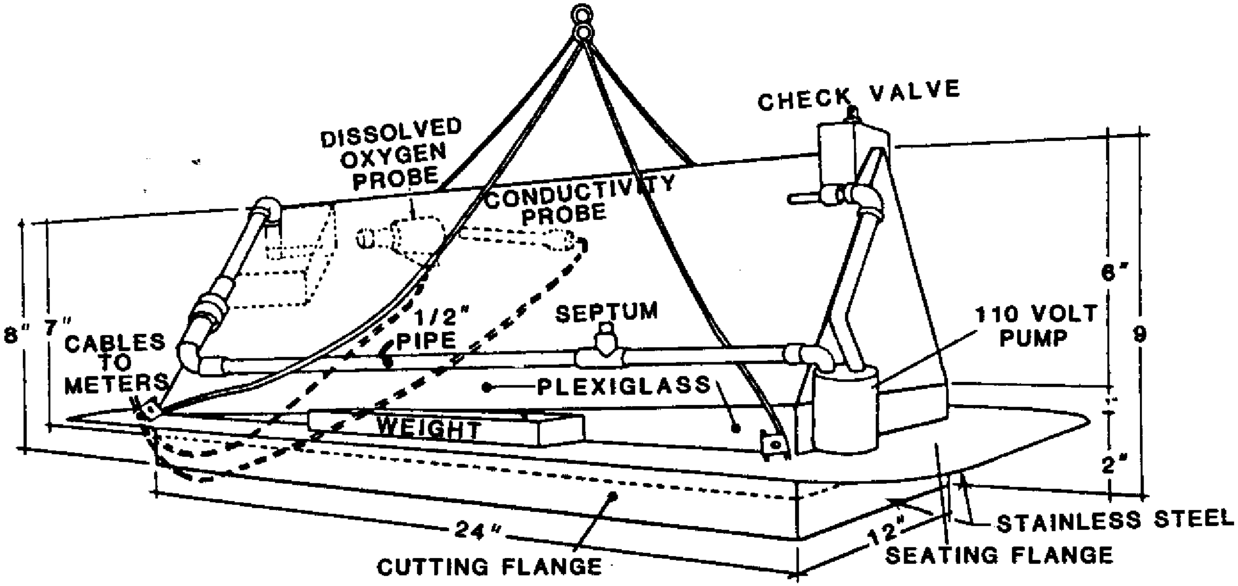
METHODOLOGY

Field Techniques

Considering the views presented in the literature review, it is more desirable to reduce the errors found in the field measurements and to account for empirical relationships of the variables rather than to accept the inherent errors posed with the laboratory respirometers.

The SOD chambers used in this investigation were those used by Lucas and Thomas (1971) to measure the SOD rate of the central basin in 1970 (Figure 6). One opaque and one translucent chamber were used simultaneously to measure any possible photosynthetic effect on the SOD. A submersible pump was attached to the chamber's seating flanges for water circulation within the chamber. The velocity of the water within the chamber was determined using a 1 percent rhodamine dye solution which was injected into the chamber. The typical velocity within the chamber was 5.0 cm/sec (similar to that in the central basin hypolimnion), the flow rate through the chamber was 0.59 l/sec, and the time for complete circulation of the water within the chamber was 22 seconds.

The DO and temperature were monitored by a Martek electronic probe which was internally-housed (Figure 6). The cutting flanges isolated a known portion of the sediment and the seating flanges prevented the chamber from sinking into the soft sediments. In harder substrates, weights could be added to the seating flanges to allow the chamber to properly seal itself. The one-way check valve allows gases which may have evolved from the sediments to pass out of the chamber. These gases may otherwise be trapped inside the chamber and thus interfere with the oxygen probe and original volume of water.



SEDIMENT OXYGEN DEMAND CHAMBER.

Figure 6. Sediment Oxygen Demand Chamber Developed by Lucas and Thomas (1971) and Used for the Present Study.

To measure the SOD rate in the field, the two chambers were lowered from the R/V Hydra (Ohio State University's 65-foot research vessel), just below the water surface and the dissolved oxygen meters were allowed to equilibrate for at least 20 minutes. The meters were then calibrated at a depth of 1 m with the Azide modification of the Winkler method (Standard Methods 1975). The submersible pumps were activated and the chambers were gently tilted back and forth to expel all the air that may have been trapped in the system.

Once the DO meters were calibrated and the pumps were operational, the chambers were lowered to approximately 2 m from the bottom and were manipulated back and forth to replace the entrained surface water with the bottom water. At this time the pump was shut off and the chamber was lowered and placed gently on the bottom by SCUBA divers. Any sediments that were uplifted during placement of the chamber were allowed to settle for 15 minutes before the pump was activated again. The dissolved oxygen and temperature were monitored for 10- or 15-minute intervals for approximately two hours. Previous measurements indicate that Lake Erie's sediments do exhibit a measureable oxygen demand, so if there was not an apparent drop in dissolved oxygen after the initial few observations, the chamber was reset at another location. The most common reason for the DO not to be depleted from within the chamber was due to a poor seal between the chamber's flanges and the sediment, allowing oxygenated hypolimnetic water to enter the system. The SOD rate measured in the chambers is expressed areally by the units g $O_2/m^2/day$.

The hypolimnetic WOD rate was measured by incubating sets of light and dark BOD bottles for 12 and 24 hours. The bottles were placed in the water column at one meter below the thermocline and at one meter above the sediments. The mean amount of dissolved oxygen consumed in these bottles during the incubation period represents the oxygen demand in the water and is expressed in volumetric units of g O_2/m^3/day. Due to significant oxygen production in many of the dark bottles, averages of the two depths for only the 24 hour light bottle measurements were used in the calculations.

The sampling sites chosen were those used in the Lake Erie Nutrient Control Program (Herdendorf 1980) by the Center for Lake Erie Area Research (CLEAR). The stations are indicative of the natural depth distribution of the basins since the sampling sites significantly ($\alpha = 0.05$) increased from the western to eastern basins similar to the basin morphometry (Sly 1976).

The parameters sampled in 1978 included SOD, depth and temperature (InterOcean CSTD Model 514D); dissolved oxygen (Azide modification of the Winkler method; Standard Methods 1975); extinction depth (Lambda meter and submarine photometer); benthic macroinvertebrates (see Appendix 1); grain-size distribution (see Table 1); sediment total volatile solids and sediment total solids (Standard Methods 1975); sediment total phosphorus, hypolimnetic total phosphorus, sediment total iron and sediment total manganese (Standard Methods 1975; Technicon AutoAnalyzer II); and sediment aerobic heterotrophs (see Appendix 1).

The parameters measured in 1979 were SOD, depth and temperature (InterOcean CSTD Model 514D); dissolved oxygen (Azide modification of the Winkler method); water oxygen demand (see Appendix 1); soluble and total nutrients (Standard Methods 1975; Technicon AutoAnalyzer II); alkalinity (Standard Methods 1975); chlorophyll and phophytin pigments (90% acetone extraction and Varion spectrophotometric method); and sediment aerobic heterotrophs (see Appendix 1).

Data Reduction and Analysis

The oxygen readings taken from 10- to 15-minute intervals were entered into a linear regression to obtain a slope. This slope represents the SOD rate expressed in units of milligrams O_2 per liter per minute (mg O_2/l/min) which is converted to grams O_2 per square meter per day (g O_2/m^2/day) by the formula:

$$\mathrm{SOD} = 1440SV/10^3A$$

where SOD is the sediment oxygen demand (g O_2/m^2/day);

S is the slope of some portion of the curve (mg/l/min);

V is the volume of the chamber (liters); and

A is the bottom area of the chamber (square meters).

Although both chambers were built to the specification shown in Figure 6, the dark chamber is only 13.5 l in volume, while the light chamber is 16 l. The bottom areas of both chambers were 0.186 m^2. Therefore, the specific formula for the light chamber is:

$$\mathrm{SOD} = 128.7S - \frac{.016}{.186}\mathrm{WOD}$$

and the formula for the dark chamber is:

$$\mathrm{SOD} = 112.5S - \frac{.0135}{.186}\mathrm{WOD}$$

where S equals the slope of some portion of the curve (mg/l/min);

and WOD is the water column oxygen demand found in the bottles.

Caution was taken when selecting the portion of the curve to be analyzed to be sure a representative segment was chosen. Generally the most stabilized linear portion of the curve was applied to the regression; however, this at times involved subjectivity. Three types of SOD curves were encountered in this investigation (Figure 7). Type 1 was completely linear and found only in well-oxygenated waters with little sediment disturbance upon placement of the chamber. But the more common curve was Type 2 which exhibits two separate rates. First, there is a rapid initial oxygen uptake due to the disturbance to the sediments when the chamber was put into place. This increased rate was due to exposing readily oxidizable materials which perhaps indicates that a 15-minute settling time for the sediments may not have been long enough. Secondly, the curve then shows a decreased rate, presumably once the sediments had become fully oxidized. This second rate, which reflects relatively stable sediments, is the one used to calculate the SOD rate. The third type of curve encountered, Type 3, was seen only under low hypolimnetic oxygen concentrations (during cruise three; August 16-22) and is similar to an exponential oxygen uptake. The high initial rate is once again due to disturbed sediments, while other portions are influenced by the oxygen concentration of the water. Oxygen availability was found to limit the oxygen uptake by the sediments by slowing the diffusion of oxygen to the sediments through the boundary layer. This curve is sometimes smoothed out as seen in Figure 8, which shows an exponential oxygen uptake. However, it appears that below 3 mg O_2/l the actual SOD rate in the Lake Erie sediments is quite similar whether or not a linear or exponential function is considered.

To be able to directly compare the volumetric WOD rates with the areal SOD rates they must be expressed in similar units. To allow for an estimate of the oxygen depletion rate, the SOD rates are corrected to volumetric units by dividing the areal SOD rate by

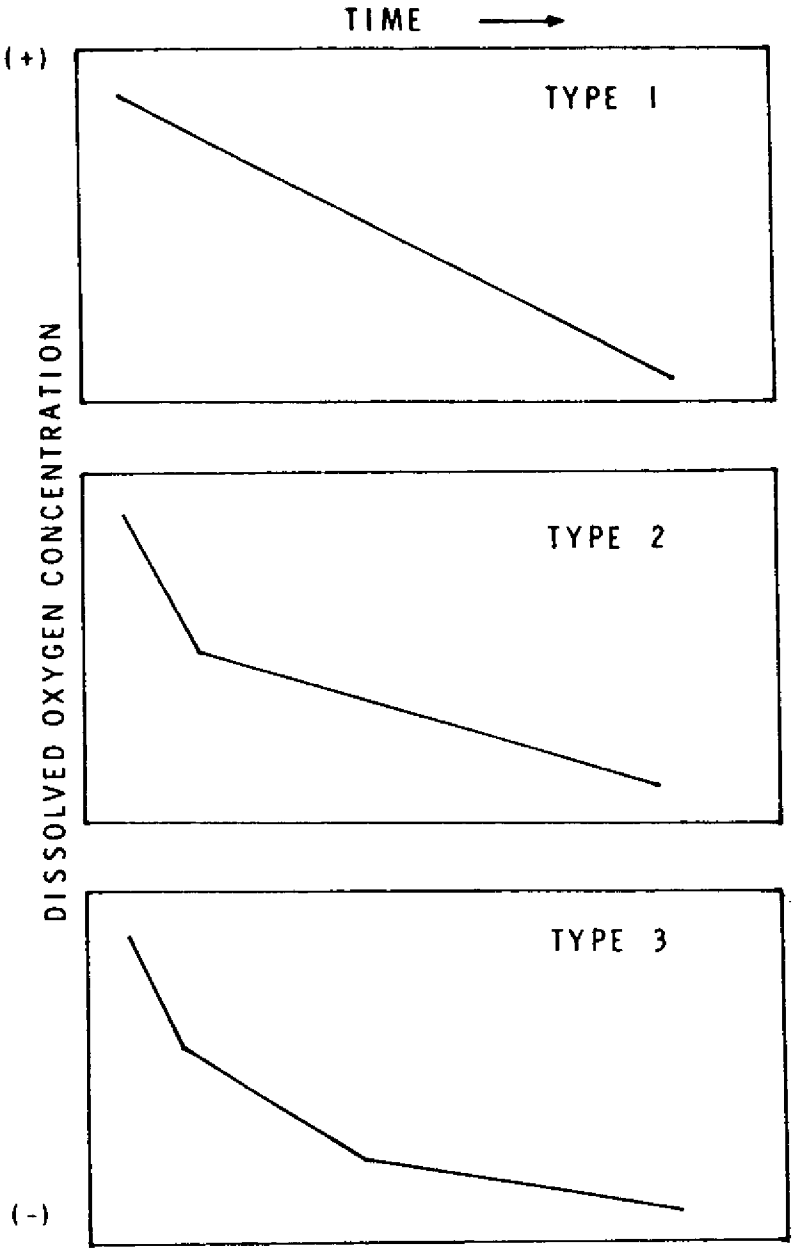


Figure 7. Typical oxygen depletion curves obtained from sediment oxygen demand chambers.

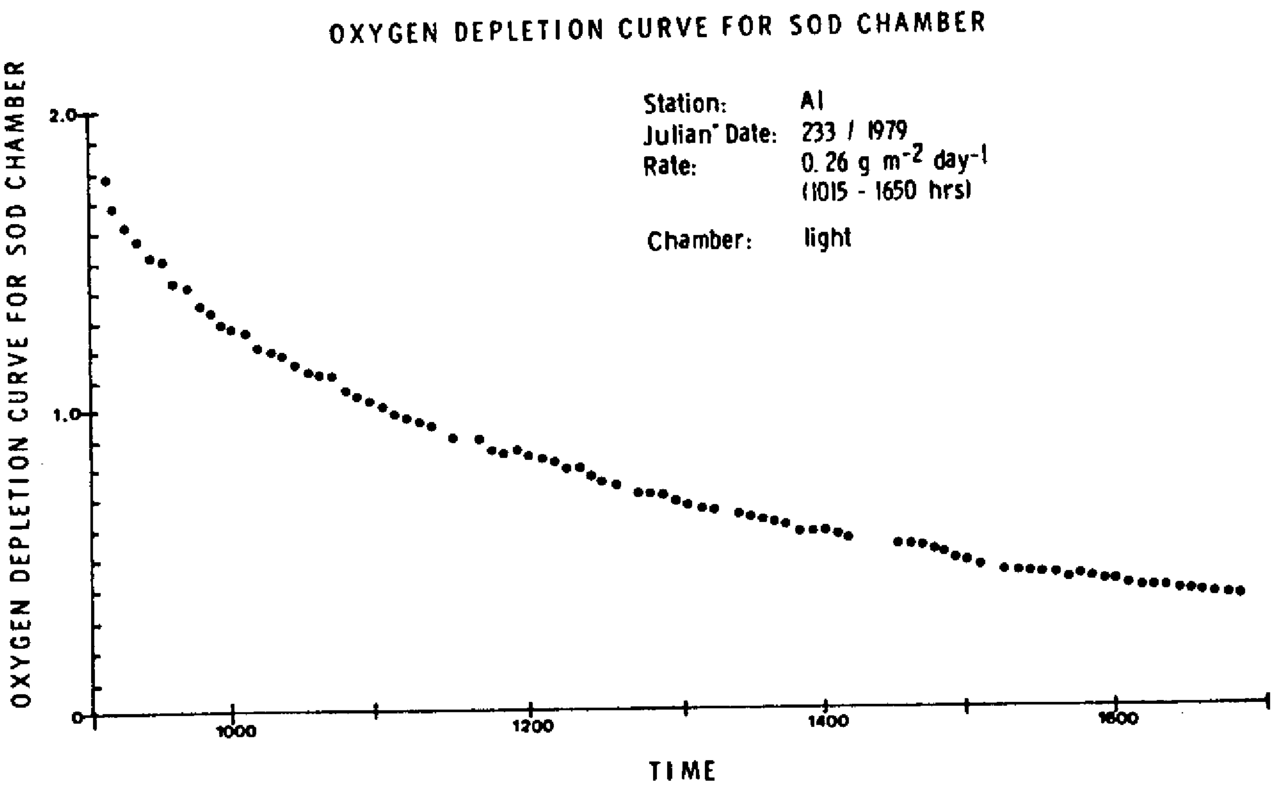


Figure 8. Oxygen Depletion Curve for SOD Chamber Demonstrating the Curvature of the Slope Below 2 mg O_2l^{-1}.

the hypolimnion thickness. The thicker the hypolimnion, the less effect the SOD will have on the overlying water (Zapotosky and Herdendorf 1980).

Aside from determining the SOD rates by fitting the points on the curve to a statistical linear regression technique (Barr et al. 1976), a comparison of the relationships of the variables was processed with the use of a statistical program package entitled "Statistical Analysis System" (Barr et al. 1976). The 1978 and 1979 data were processed as separate data sets due to the difference in the parameters enumerated, but primarily due to the fact that the 1978 data set was spatially distributed while the 1979 data was temporarily distributed. A multiple stepwise regression technique (Barr et al. 1976) has been used to compare the independent variables to the dependent variable, SOD, for each of the two years.

In order to determine which factor(s) have an influence on SOD rates, a series of variables was analyzed and listed in Table 1. The criteria for choosing which variables were used in the predictive equations were determined by considering several factors which included the maximum r^2 improvement, the mean sum of squares, degrees of freedom in the error term, and the probability. If a variable was chosen which clearly did not relate to the SOD rate in any way, it was discarded and a new model was tested.

To determine if there was a relationship between any variable and the particular basin that was sampled, a one-way analysis of variance (ANOVA) was run using the programs from the Statistical Analysis System (Barr et al. 1976). The one-way ANOVA will indicate any significant ($\alpha = 0.05$) difference between the means of the variables in each basin, represented by the probability that a difference in the mean values does not exist (PR< F) and the correlation coefficient (r). The coefficient of determination (r^2) is the percentage of the variability in the dependent parameter that is caused by the independent variable(s).

RESULTS

1978 Experiments

SOD Rates. The distribution of SOD rates in Lake Erie is shown in Figure 9. In general, the SOD rates correspond to the sedimentary basins (Figure 2) with the higher SOD rates found in zones of deposition. A list of the SOD rates and related data for each station appears in Table 4.

Table 5 contains the mean parameter values for each basin. The mean SOD rates for the western, central and eastern basins were 2.45, 1.08 and 1.14 g $O_2m^{-2}d^{-1}$, respectively. From a one-way analysis of variance (ANOVA) it was determined that there was no significant difference ($\alpha = 0.05$) in the mean SOD rates for the central and eastern basins, but these two rates did display a significant difference from the mean SOD rate of the western basin. The rates for each station correlated with the basin sampled had a correlation coefficient of $r = 0.64$, meaning that the SOD rate generally increased from the eastern to western basin. In other words, 41 percent ($0.64^2 \times 100$) of the variability in the SOD rate of Lake Erie can be explained by which basin was sampled when all the parameters for each basin are included in the analysis.

SOD Rate and Temperature. The mean bottom temperatures for the stations sampled in the western, central and eastern basins were 23.9°C, 10.5°C and 11.5°C, respectively (Table 5). The mean hypolimnetic temperatures in the deeper waters of the eastern and central basins were 5.5°C and 9.4°C. The correlation coefficient between the SOD rate and the temperature of the bottom waters ($r = 0.53$, $P = 0.002$) suggests that the major factor relating the SOD rate to the basin sampled was the temperature difference between the basins. Considering these temperature differences, as the SOD rates were

TABLE 4

SEDIMENT OXYGEN DEMAND RATES BY STATION IN LAKE ERIE - 1978[1]

Station	Basin	SOD rate[2] g $O_2 m^{-2} d^{-1}$	Hypo[3] Temp °C	DO[3] Hypo mg/l	Date	Sample Time
010	E	1.20 L	6.0	7.5	215	1810-2010
011	E	1.00 L	10.0	5.0	215	2220-2335
014	E	0.98 L	4.5	8.95	215	2245-0015
015	E	1.94 D	5.5	9.95	214	2315-0030
024	C	0.41 L	8.2	6.1	216	0020-0105
024	C	0.86 D	8.9	6.1	216	2320-0105
026	C	0.77 D	9.0	9.7	213	1630-1830
028	C	0.44 C	9.5	7.7	213	1110-1210
028	C	0.64 D	9.5	7.7	213	1010-1055
030	C	0.97 L	10.2	8.3	212	1945-2130
042	C	1.07 L	8.5	6.00	217	2019-2134
042	C	1.74 D	8.7	6.00	217	1949-2104
050	C	0.60 L	16.0	6.8	218	0910-0955
050	C	1.83 D	18.0	6.8	218	0910-1010
052	C	0.72 L	15.7	5.0	208	1405-1520
052	C	1.72 L	11.5	7.10	167	1257-1340
052	C	1.15 L	12.8	5.0	150	1325-1440
057	W	3.19 D	24.1	6.0	233	1600-1715
057	W	2.18 L	24.0	7.9	233	1630-1800
060	W	2.07 D	23.6	7.7	234	0930-1145
060	W	2.34 L	23.7	7.7	234	1000-1145
062	E	1.00 D	23.2	7.95	216	1240-1425
064	E	2.14 L	19.7	8.0	213	2245-0015
064	E	1.60 D	19.7	8.0	213	2315-0030
073	C	0.98 D	10.5	4.8	217	1155-1340
073	C	1.68 L	10.5	4.8	217	1145-1310
078	C	1.05 D	8.9	6.15	217	0625-0710
079	C	1.28 L	8.8	8.00	212	1430-1530
080	E	0.91 L	15.7	7.50	214	1800-1915
080	E	1.17 D	16.0	7.50	214	1745-1900
082	C	0.33 L	12.0	3.80	208	1820-1935
083	C	1.17 D	10.0	4.60	218	1313-1458
R	C	1.11 D	8.7	5.90	217	1532-1717
R	C	1.62 L	9.2	5.90	217	1547-1732

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[1] Doesn't include data which could not be applied to derive an SOD rate.

[2] L = translucent chamber (light)
D = opaque chamber (dark)

[3] Sample values were averaged from above sediment to thermocline.

TABLE 5
MEAN VALUES FOR THE VARIABLES IN EACH BASIN - 1978

Variable	n	Western	Central	Eastern
SOD (g O_2/m/day)	36	2.45[1]	1.08	1.14
SOD @ 10°C	36	1.29	1.10	1.22
Day (Julian)	54	183.00	204.00	214.00
Depth (meters)	54	10.21[1]	19.14[1]	27.64[1]
Surface (°C) Temperature	54	18.70	21.00	22.60
Bottom (°C) Temperature	54	23.90[1]	10.50	11.50
Surface DO (mg O_2/l)	54	9.50	9.10	8.60
Bottom DO (mg O_2/l)	54	7.30	6.50	7.90
Total Number Benthos (m^2)	36		1870.00	5150.00
Number Oligochaetes (m^2)	36		970.00	3500.00
Number Diptera (m^2)	36		450.00	200.00
Number Amphipods (m^2)	36		70.00	52.00[1]
PHI (sediment)	36		6.40	940.00
Percent Gravel	36		4.60	0.20
Percent Sand	36		33.10	15.87
Percent Silt	36		33.49[1]	49.20[1]
Percent Clay	36		28.49	34.55
Percent TVS (Sediment)	33		5.80[1]	8.30[1]
Percent TS (Sediment)	33		52.00	47.20
Total Phosphorus Sediment[2]	33		436.75	370.10
Total Phosphorus in Hypolimnion[3]	37		51.86	45.32
Total Manganese in Sediment[2]	33		532.35	652.01
Total Iron in Sediment[2]	33		21,348.00	21,820.00
Bacteria in Sediment[4]	37		21,275.00[1]	43,500.00[1]
Percent Light Reaching Sediments	36		0.10	0.27

---

[1] Indicates a significant (α=.05) difference between the mean variable values of those basins.

[2] Units are in micrograms per gram of sediment

[3] Units are in micrograms per liter.

[4] Units are in cells per 15 g of sediment sample

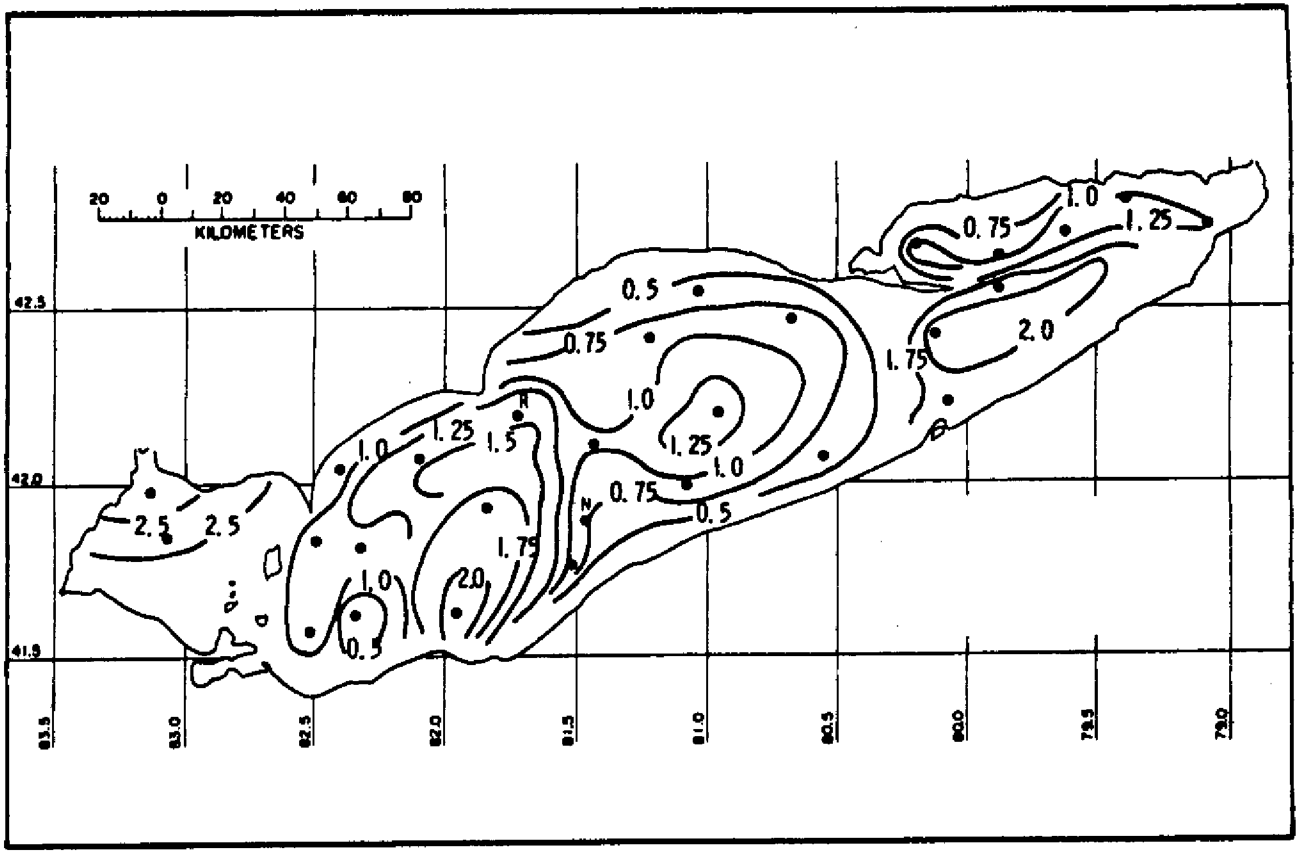

Figure 9. Lake Erie Sediment Oxygen Demand Rates - 1978 (g O_2 $m^{-2}d^{-1}$).

adjusted to a constant temperature of 10°C throughout the lake, no correlation between the SOD rate and basin was found ($r = 0.14$, $P = 0.71$). This demonstrated that the temperature corrected SOD rate takes into account the effects of temperature since we would expect there to be a small and insignificant correlation between temperature-corrected rates and the basin sampled. Therefore, in the presentation of the results and discussion of this paper, the temperature-corrected SOD rates for the 1978 data will be used.

Correlation of Selected Variables with the SOD Rate. The following analysis utilizes the data from only the central and eastern basins. The mean number of benthic macroinvertebrates per square meter in the eastern basin was 5150 and in the central basin, 1870 (Table 5). An isoplethic distribution map of the total number of benthos is shown in Figure 10 and is expressed in benthos per ponar grab sample (23 cm x 23 cm) for ease of representation. A list of the benthos (oligochaetes, diptera, amphipods) appears by station in Table 6. Oligochaetes averaged 3500 per square meter in the eastern basin comprising 89 percent of the total benthos found. The logarithmic number of total benthos accounts for 46 percent ($r = 0.68$, $P = 0.0001$) of the variability in the SOD rate and the oligochaetes can explain 38 percent ($r = 0.61$, $P = 0.0009$) of the SOD rate variability when considered separately using simple regression techniques (Table 7).

The mean values for the physical and chemical properties of the sediments in the central and eastern basins appear in Table 5. In addition, the station values for the mean grain size including the percent gravel, sand, silt and clay of the sediments are listed in Table 8.

TABLE 6

BENTHIC MACROINVERTEBRATES BY STATION IN LAKE ERIE - 1978

Station	Date	Basin	Total Benthos*	Oligochaetes	Diptera	Amphipods
010	215	E	322	190	20	90
011	215	E	---**	---	---	---
014	215	E	317	129	2	70
015	214	E	812	803	5	4
018	214	E	473	262	19	166
024	216	C	79	15	42	2
026	213	C	114	59	25	1
028	213	C	25	15	2	0
030	212	C	108	47	13	0
032	212	C	87	50	22	0
035	209	C	13	7	3	0
042	217	C	117	109	8	0
045	209	C	149	102	0	0
048	218	C	---**	---	---	---
050	218	C	147	72	75	0
052	208	C	78	39	28	0
062	216	E	14	9	5	0
064	213	E	101	66	9	1
073	217	C	63	50	4	0
078	217	C	156	67	61	0
079	212	C	113	95	7	0
080	214	E	150	27	18	86
082	208	C	21	10	9	0
083	218	C	124	55	70	0
N	209	C	115	71	7	0
R	217	C	156	40	10	1

---

*Benthos are presented as organisms per ponar grab (23 cm^2). To convert to benthos per m^2, multiply by 18.91.

**Sample not taken due to rocky substrate.

TABLE 7

VARIABLES CORRELATED WITH SEDIMENT OXYGEN DEMAND-1978

		SOD (ambient)		SOD (10°C)	
Variable	n	r	P	r	P
Hypolimnetic Temperature	33	0.51	0.002	-0.14	0.45
Sediment Light (%)	25	-0.40	0.05	-0.40	0.05
Benthos (Total)	28	0.37	0.05	0.62	0.0007
Benthos (Log)	28	0.48	0.01	0.68	0.0001
Oligochaetes	28	0.39	0.04	0.61	0.0009
Sediment (Phi)	27	0.42	0.03	0.58	0.002
Percent Gravel	27	-0.33	0.08	-0.31	0.12
Percent Sand	27	-0.32	0.08	-0.50	0.01
Percent Silt	27	0.38	0.05	0.49	0.01
Percent Clay	27	0.39	0.04	0.60	0.001
TVS (%)	25	0.39	0.05	0.51	0.01
TS (%)	25	-0.46	0.01	-0.56	0.004
Sediment P	24	0.22	0.31	0.39	0.06
Sediment Mn	24	0.25	0.23	0.53	0.007
Sediment Fe	24	0.22	0.31	0.39	0.06

n=number of observations
r=correlation coefficient
p=significance probability of the F-value

TABLE 8

SEDIMENT GRAIN SIZE DISTRIBUTION BY STATION - 1978

Station	Date	Basin	PHI	Percent Gravel	Percent Sand	Percent Silt	Percent Clay
010	215	E	9.02	0.00	0.57	53.00	46.00
011	215	E	---*	---	---	---	---
014	215	E	9.46	0.00	0.75	47.00	52.00
015	214	E	9.18	0.00	0.76	50.00	49.00
018	214	E	9.04	0.00	2.76	52.00	46.00
024	216	C	5.38	0.15	57.00	24.00	19.00
026	213	C	4.40**	0.09	78.00	13.00	9.00
028	213	C	-0.76	61.00	37.00	0.43	0.56
030	212	C	7.41	0.00	6.05	63.00	31.00
032	212	C	5.95	0.24	33.60	44.00	22.00
035	209	C	---*	---	---	---	---
042	217	C	9.60	0.00	1.64	40.00	58.00
045	209	C	8.64	0.90	6.17	46.00	47.00
048	218	C	---*	---	---	---	---
050	218	C	2.34	1.18	91.00	4.65	3.21
052	208	C	8.62	0.00	2.09	53.00	45.00
062	216	E	5.31	1.00	44.00	38.60	16.40
064	213	E	6.05	0.21	36.00	45.00	19.00
073	217	C	8.61	0.03	0.93	52.00	44.00
078	217	C	8.72	0.64	3.92	48.00	47.00
079	212	C	4.31	0.21	80.00	11.00	8.79
080	214	E	7.84	0.14	6.25	63.00	29.00
082	208	C	3.83	0.44	83.00	7.55	8.67
083	218	C	6.18	0.19	40.00	37.00	23.00
N	209	C	9.10	0.00	3.37	44.00	53.00
R	217	C	9.47	0.00	0.67	47.00	53.00

*Sample not analyzed
**PHI value is estimated

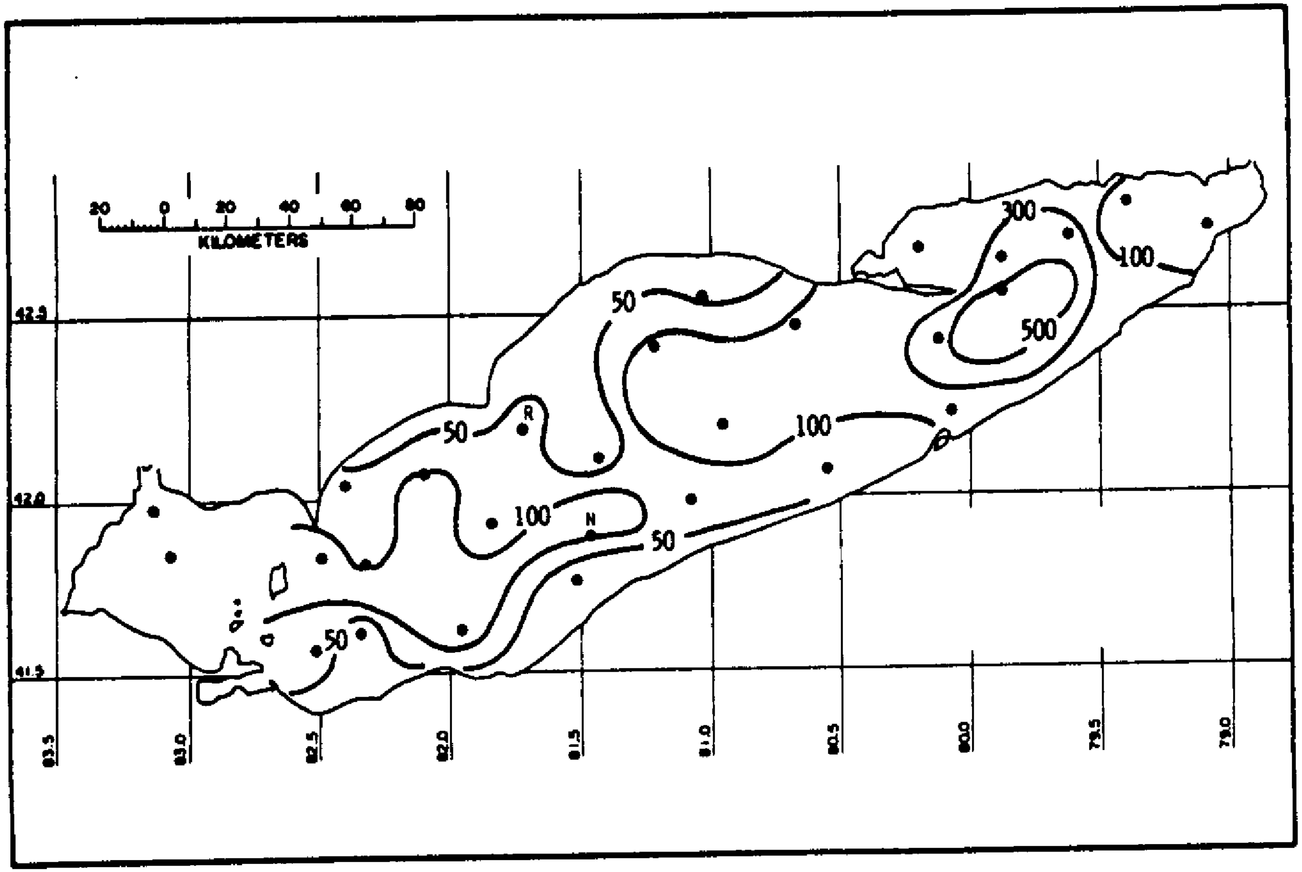

Figure 10. Benthic Macroinvertebrate Distribution in Lake Erie - 1978 (23 cm^2).

As expected, the depositional zones of the lake contained the smaller grain sizes as shown in Figure 11. Significant correlations between the SOD rate and the sediment grain size appear in Table 9. The PHI value of the sediments (PHI, 0 = $-\log_2 E$, where E is the diameter of the grain size in mm) was positively correlated with the SOD rate (r = 0.58, P = 0.002) indicating that the higher PHI values corresponded to the higher SOD rates. In other words, the particles with the smallest diameter, such as the clays and silts, tend to display the highest SOD rate. In particular, the clay and silt fractions were positively correlated with the SOD rate (r = 0.60 and r = 0.49, respectively), and the sand and gravel fractions were negatively correlated to the SOD rate (r = -0.50 and r = -0.31, respectively).

The total volatile solids (TVS) and the total solids (TS) content of the sediments ranged from 2 to 11 percent and 23 to 74 percent, respectively. The mean TVS and TS percentages for the central basin were 5.8 and 52 percent and for the eastern basin were 8.3 and 47.2 percent, respectively. The TVS in the sediments had a positive correlation (r = 0.51, P = 0.01) with the SOD rate while the TS of the sediments correlated negatively with the SOD rate (r = -0.56, P = 0.0004).

Isoplethic distribution maps of the total iron, total phosphorus and total manganese in the sediments, as well as the total phosphorus in the hypolimnetic water appear in Figures 12-15. A list of these parameters by station is presented in Table 10. There were no significant differences between any of these parameters and the basin (Table 5). The SOD rate correlated significantly with the three sediment chemical measurements, but not with the total phosphorus in the hypolimnion (r = -0.18, P = 0.39). The SOD rate correlations with the total phosphorus, manganese and iron in the sediments are r = 0.39 (P = 0.06), r = 0.53 (P = 0.007) and r = 0.39 (P = 0.06), respectively (Table 7). Also, these

TABLE 9

CORRELATION COEFFICIENTS BETWEEN CENTRAL AND EASTERN BASIN SOD RATES AND SEDIMENT GRAIN SIZE - 1978

n=28

	SOD		SOD @ 10°C	
	r	P	r	P
PHI	0.42	0.03	0.59	0.002
% Gravel	-0.33	0.08	-0.31	0.12
% Sand	-0.32	0.08	-0.50	0.01
% Silt	0.38	0.05	0.49	0.01
% Clay	0.39	0.04	0.60	0.001

r = correlation coefficient
P = probability

TABLE 10

INORGANIC CHEMICAL DISTRIBUTION BY STATION - 1978

Station	Date	Basin	Total Phosphorus Sediment (ppm)	Total Manganese Sediment (ppm)	Total Iron Sediment (ppm x 10^{-3})	Total Phosphorus Hypolimnion (ppb)
010	215	E	480	710	27	79
011	215	E	---*	---	---	20
014	215	E	490	832	23	82
015	214	E	615	1107	25	38
018	214	E	525	751	31	47
024	216	C	219	260	14	22
026	213	C	525	281	9	72
028	213	C	255	489	14	120
030	212	C	280	289	16	48
032	212	C	402	283	17	28
035	209	C	424	327	25	19
042	217	C	514	623	38	20
045	209	C	469	494	34	48
048	218	C	---*	---	---	23
050	218	C	204.5	169	7	44
052	208	C	494	457	35	65
062	216	E	263	566	15	18
064	213	E	248	331	14	61
073	217	C	577	538	26	20
078	217	C	553	465	28	24
079	212	C	953	253	11	148
080	214	E	535	584	25	28
082	208	C	419	331	26	30
083	218	C	233	306	10	23
N	209	C	406	549	35	30
R	217	C	449	436	37	---

*Measurements not taken

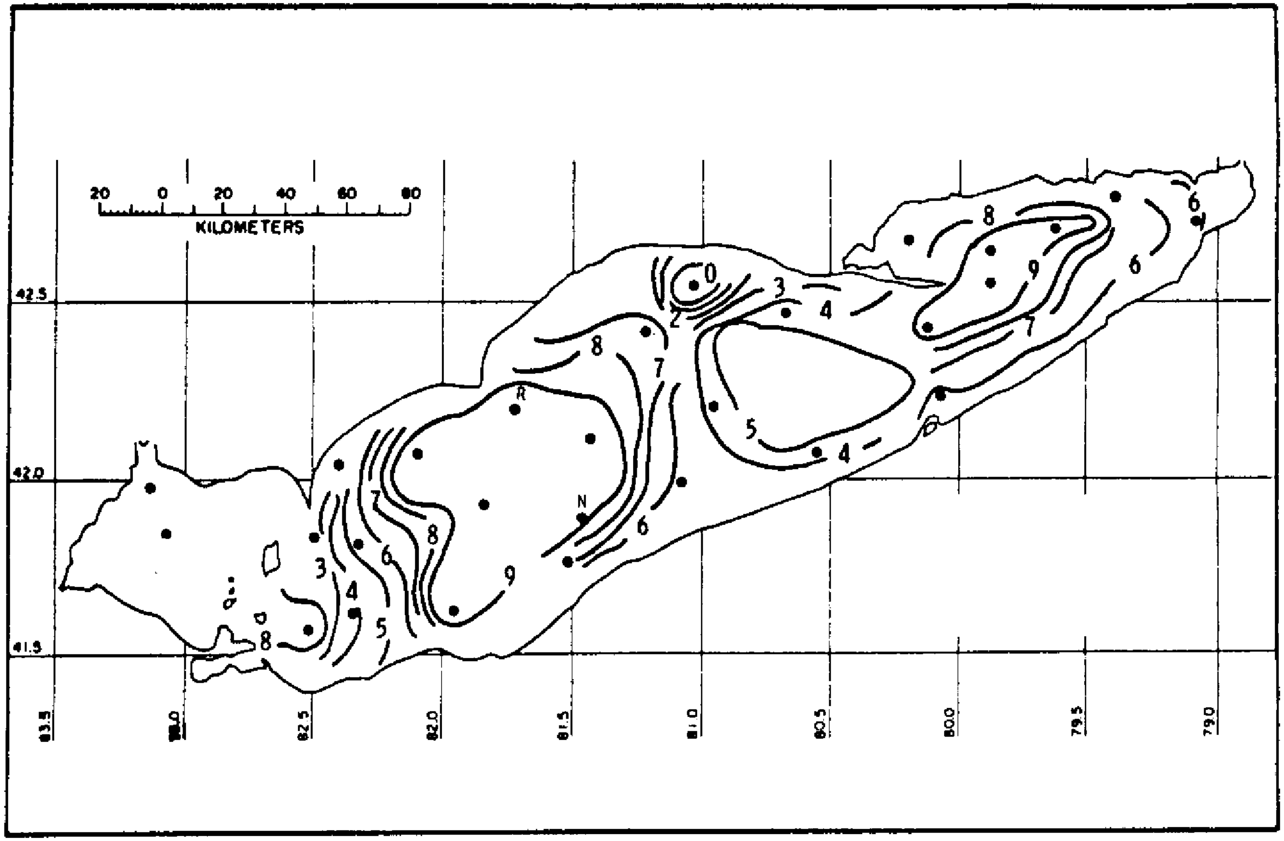

Figure 11. PHI Distribution in Lake Erie Sediments.

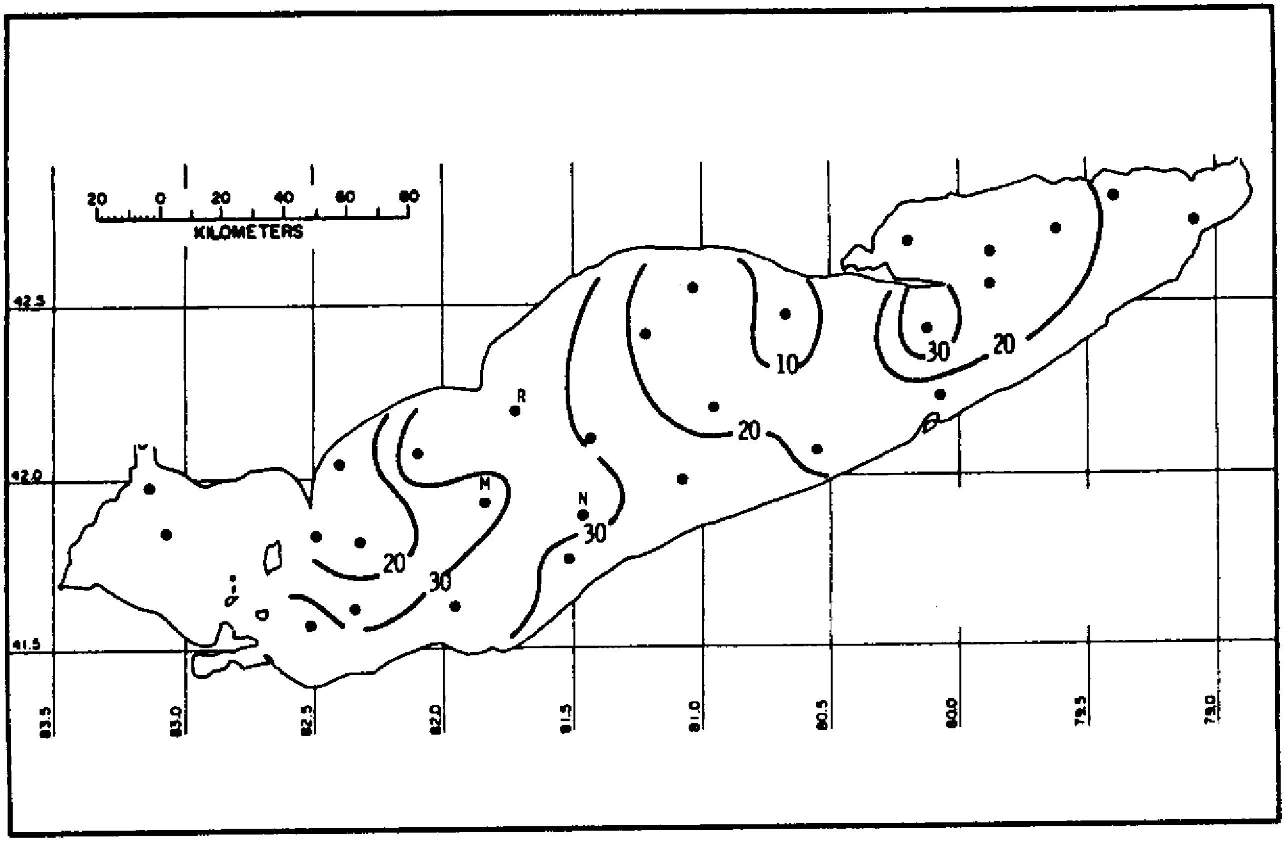

Figure 12. Total Iron Distribution in Lake Erie Sediments - 1978 (ppm x 10^{-3}).

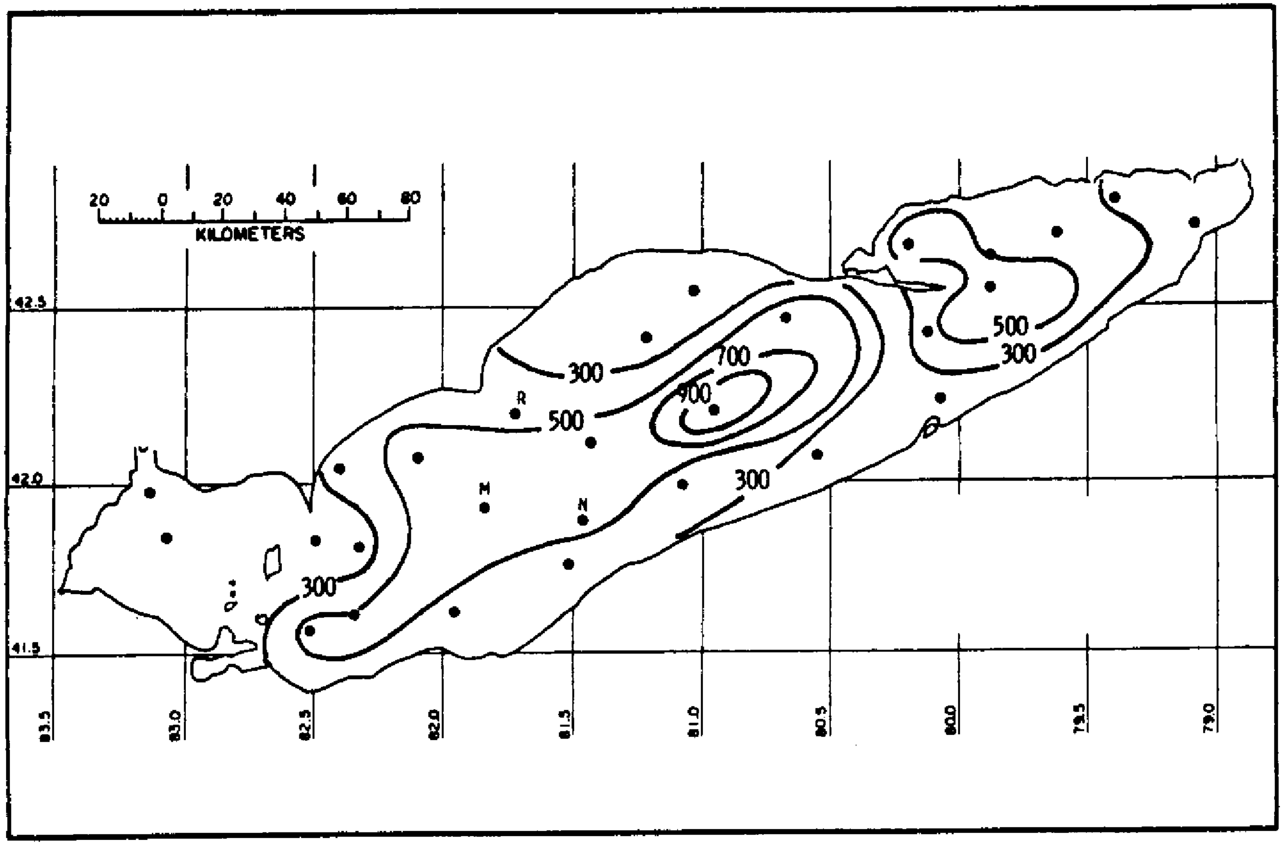

Figure 13. Total Phosphorus Distribution in Lake Erie Sediments - 1978 (ppm).

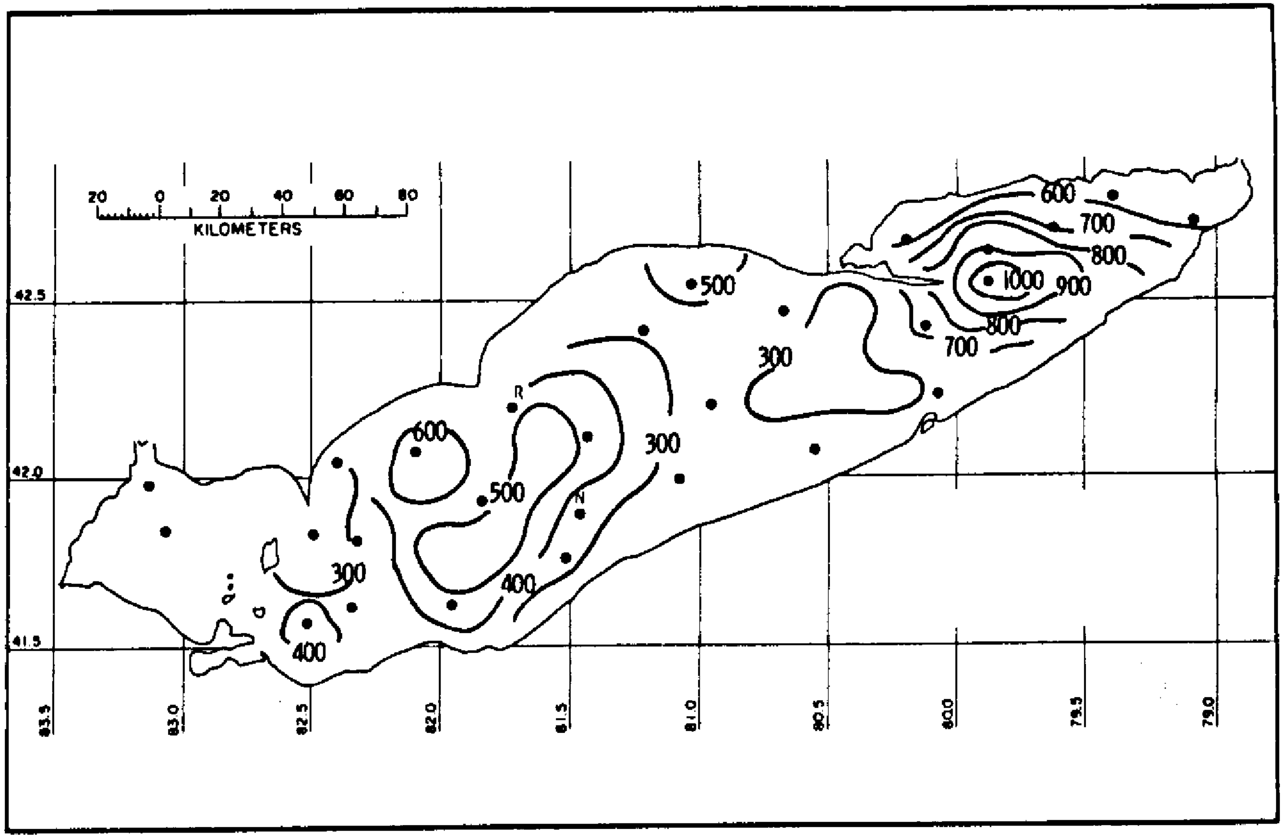

Figure 14. Distribution of Total Manganese in Lake Erie Sediments - 1978 (ppm)

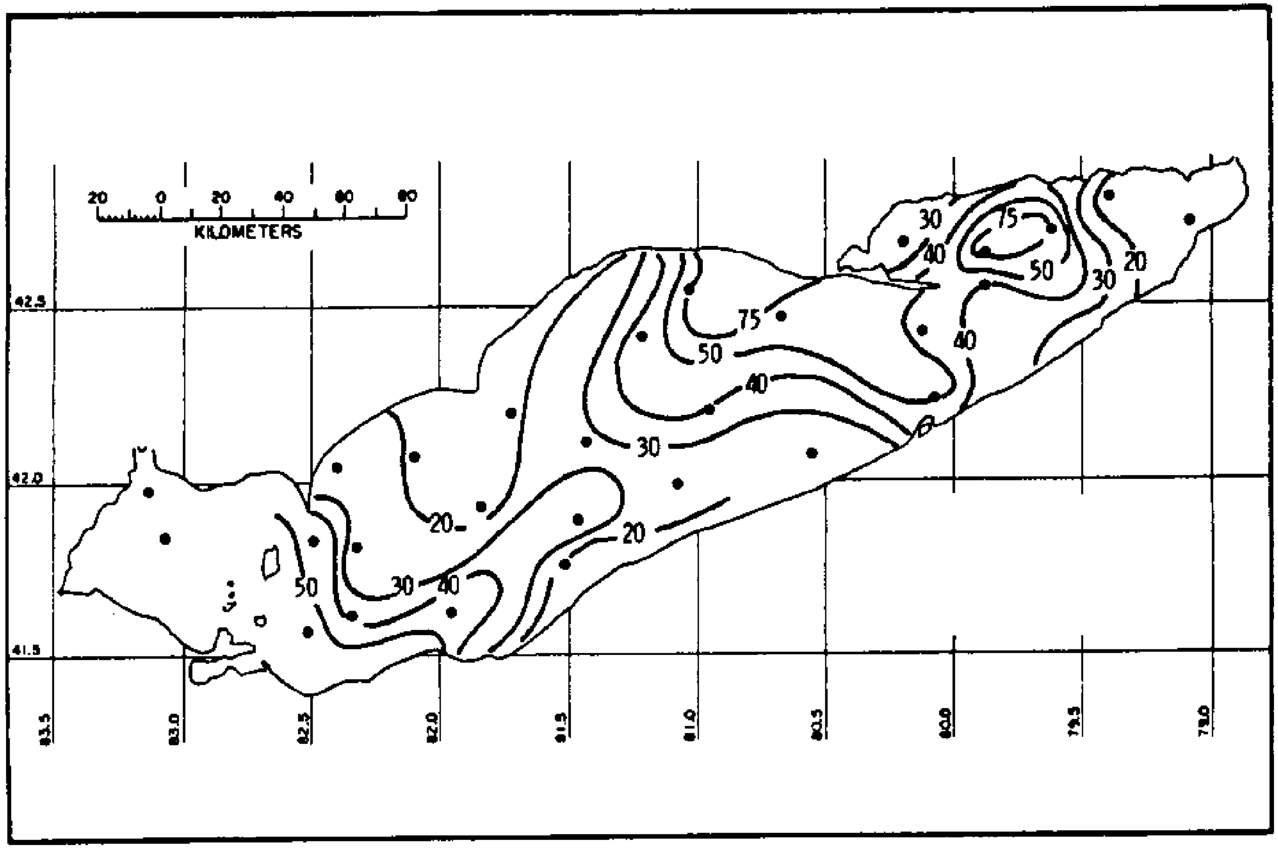

Figure 15. Total Phosphorus Distribution in Lake Erie Bottom Waters - 1978 (ppb).

three variables are the only parameters which were significantly correlated with the temperature-corrected SOD rate but were not correlated with the ambient SOD rate.

The percent incident light reaching the sediment ranged from 0 to 1.24 percent at the stations sampled with the mean value for the central basin being 0.10 percent, and a mean for the eastern basin of 0.27 percent (Table 5). There was no significant difference between the mean light values for the two basins ($P = 0.50$). The correlation of the percent light reaching the sediments with the SOD rate was $r = -0.40$ ($P = 0.05$) showing that as the amount of light increased the SOD rate decreased (Table 8). The station values for the percent incident light reaching the sediments are shown in Table 11.

Light (translucent) and dark (opaque) chambers were used to monitor diurnal changes that may occur in the SOD rate due to algal photosynthesis, by conducting measurements throughout a twenty-four hour period and by noting differences between the SOD rates in the light and dark chambers. No correlation was found between the time of day sampled and the SOD rate ($r = 0.09$, $P = 0.62$). Using an ANOVA test, no significant difference ($\alpha = 0.05$) was found to exist between the mean SOD rates for the two types of chambers.

The mean number of aerobic heterotrophic bacteria in the sediments was greatest in the eastern basin (43,500 cells per 15 g) and significantly different ($\alpha = 0.05$) from the numbers found in the central basin (21,275 cells per 15 g). The number of aerobic heterotrophic bacteria in the sediments has been found not to be correlated with the SOD rate in this analysis, but the results for the enumeration of the bacteria may be somewhat erroneous due to a lack of standard methods for the testing of bacterial populations in sediments (Appendix 1a and 1b). A list of the numbers of bacteria for each station

TABLE 11

LIGHT VALUES BY STATION - 1978

Station	Day	Basin	Percent Surface Light Reaching Sediment	Surface Light (micro-einsteins)	1 Percent Extinction Depth (m)
010	215	E	0.13	1500	16
011	215	E	0.00[1]	0	0
014	215	E	0.11	450	21
015	214	E	NA[2]	300	27
018	214	E	0.02	4200	17
024	216	C	0.00[1]	0	0
026	213	C	0.01	4200	14.5
028	213	C	0.25	1200	13
030	212	C	0.03	2400	11
032	212	C	0.06	1100	18.5
035	209	C	0.22	200	11
042	217	C	0.05	300[3]	7
045	209	C	0.04	1500	14.5
048	218	C	0.00[1]	0	0
050	218	C	0.03	2000	6
052	208	C	---[4]	---	---
062	216	E	0.37	3000	12
064	213	E	0.00[1]	0	0
073	217	C	0.11	4500	19
078	217	C	0.04	1000	15.5
079	212	C	0.20	3500	20
080	214	E	1.24	1700	15
082	208	C	0.57	350	15.5
083	218	C	0.12	5500	13.3
N	209	C	0.10	3000	17
R	217	C	0.10	1508	18

[1] Night time.

[2] Ran out of cable at 27 m.

[3] Sun was setting.

[4] Measurement not taken.

appears in Table 11, and a distribution map of the bacteria in the central and eastern basins is in Figure 16.

Correlations Between the TVS, TS and Grain Size of the Sediments. Presented in Table 12 are correlations between the TVS, TS and the grain size of the sediments. The PHI value of the sediments can explain 59 percent ($r = 0.77$, $P = 0.0001$) of the variability in the TVS. Also, the TS of the sediments, which are highly correlated with the TVS ($r = -0.78$, $P = 0.0001$), are negatively correlated with the SOD rate ($r = -0.42$, $P = 0.04$) indicating that the easily suspended sediments contained high fractions of volatile solids and contributed quite significantly to the SOD rate (Table 7).

Correlations of Inorganic Chemistry with the TVS, TS and Grain Size Distribution of the Sediments. The total phosphorus in the sediments (TPS) was not significantly correlated to any of these parameters; however, the other three inorganic chemical measurements showed a number of correlations (Table 13). The total iron in the sediments (TFeS) and the total phosphorus in the hypolimnetic waters (TP) were correlated with the grain size of the sediments (PHI value) showing correlation coefficients of $r = 0.71$ ($P = 0.0001$) and $r = 0.43$ ($P = 0.02$). Specifically, the TFeS and TP were correlated with the percent contribution of sand, silt and clay to the sediments. The total manganese in the sediments (TMnS) was correlated with the percent clay ($r = 0.36$, $P = 0.05$) as well as the percent sand in the sediments ($r = -0.34$, $P = 0.06$).

Although the TMnS did not correlate very well with the sediment grain size distribution, it displayed a correlation coefficient of $r = 0.78$ ($P = 0.0001$) and $r = -0.53$ ($P = 0.002$) with the TVS and TS of the sediments. The TFeS also correlated with the TVS and TS with coefficients of $r = 0.62$ ($P = 0.0002$) and $r = -0.65$ ($P = 0.0001$).

TABLE 12

CORRELATION COEFFICIENTS BETWEEN TVS, TS AND GRAIN SIZE OF THE SEDIMENTS IN THE CENTRAL AND EASTERN BASINS - 1978

n=33

	PHI		Gravel %		Sand %		Silt %		Clay %	
	r*	P**	r	P	r	P	r	P	r	P
TVS	0.76	0.0001	-0.26	0.13	-0.78	0.0001	0.73	0.0001	0.75	0.0001
TS	-0.90	0.0001	0.45	0.007	0.81	0.0001	0.74	0.0001	-0.90	0.0001

*correlation coefficient
**probability

TABLE 13

SELECTED SIGNIFICANT CORRELATIONS BETWEEN THE INORGANIC CHEMICALS AND OTHER SEDIMENT PARAMETERS IN THE CENTRAL AND EASTERN BASINS - 1978

	Total Manganese Sediment		Total Iron Sediment		Total Phosphorus Hypolimnion	
	r	P	r	P	r	P
PHI	---*	---	0.71	0.0001	-0.43	0.02
% Sand	-0.34	0.06	-0.76	0.0001	0.36	0.04
% Silt	---	---	0.55	0.001	-0.45	0.01
% Clay	0.36	0.05	0.86	0.0001	-0.42	0.02
% Gravel	---	---	---	---	0.34	0.06
TVS	0.78	0.0001	0.62	0.0002	---	---
TS	-0.53	0.0023	-0.65	0.0001	---	---

*Not significant at $\alpha=0.10$.

Note: Total phosphorus in the sediments are not significantly correlated ($\alpha=0.10$) with the above parameters.

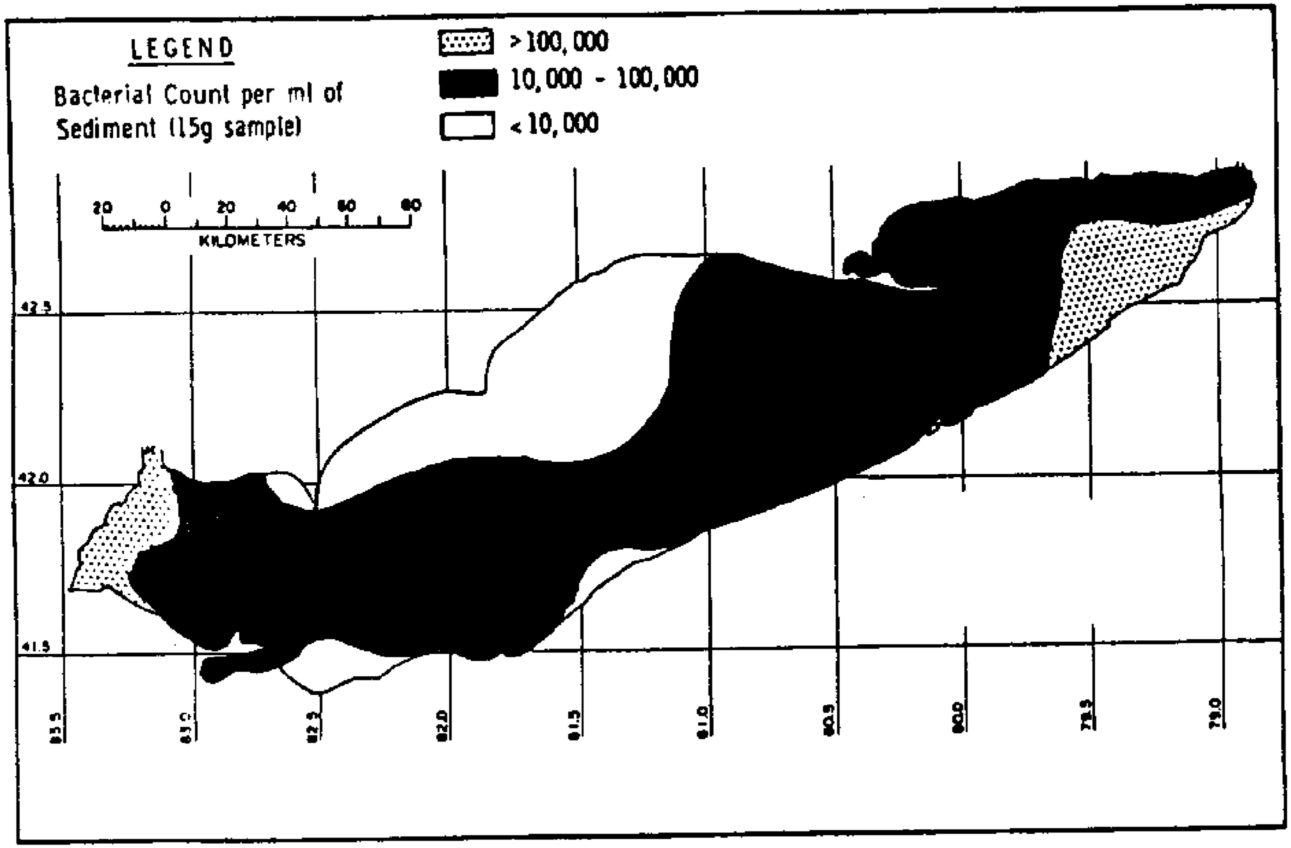

Figure 16. Aerobic Heterotrophic Bacteria in Lake Erie Sediments-1978.

Correlations with Benthos and Sediment Grain Size. A positive correlation between the PHI value and the logarithmic number of total macroinvertebrates was found (r = 0.58, P = 0.0006) indicating that the organisms tended to occupy the smaller silt and clay sediments rather than the larger gravel or sand substrates (Table 14). A sampling problem for benthos exists in sediments with large amounts of sand, gravel, rocks or hard clay so the benthic populations in such sediments may be underestimated or not even sampled. Although the correlation coefficients are not particularly strong, the oligochaetes, which comprise 86 percent of the benthic population, are found more often in sediments containing a greater proportion of clay sediments as seen by a correlation coefficient of r = 0.31 and probability of P = 0.07 between the oligochaetes and the percent clay in the sediments. This relationship is less strongly evident, as indicated by the oligochaetes correlation with the PHI value (r = 0.30, P = 0.09, Table 14).

The greater inhabitance by the amphipods of fine-grained sediments also appears to exist through correlations with the PHI value (r = 0.29, P = 0.10). A correlation coefficient of r = 0.36 (P = 0.03) between the amphipods and the percent silt content suggests a specific preference by the amphipods for silt sediments. Consequently, both the amphipods and the oligochaetes inhabited the sediments with the smallest percentage of total solids (Table 14). As mentioned previously, the smaller grain sized sediments contain a larger amount of volatile materials (r = 0.77, P = 0.0001). In addition, the correlation between the number of benthos and the total volatile solids is r = 0.49 (P = 0.0039).

The diptera, however, which were not numerically a significant part of the benthos (r = 0.02, P = 0.8989) had a slight preference for the more consolidated sediments which were the sediments which contained a greater percentage of sand.

TABLE 14

CORRELATION OF SEDIMENT GRAIN SIZE DISTRIBUTION WITH BENTHOS IN THE CENTRAL AND EASTERN BASINS - 1978

	Phi Value		Percent Gravel		Percent Sand		Percent Silt		Percent Clay	
	r	P	r	P	r	P	r	P	r	P
Total No. Benthos	0.40	0.02	-0.21	0.22	-0.32	0.07	0.31	0.07	0.40	0.02
Log No. Benthos	0.58	0.0006	-0.46	0.0059	-0.32	0.06	0.41	0.01	0.51	0.002
No. Oligochaetes	0.30	0.09	-0.14	0.42	-0.25	0.15	0.23	0.19	0.31	0.07
No. Amphipods	0.27	0.14	-0.08	0.65	-0.27	0.13	0.25	0.16	0.28	0.12
No. Diptera	-0.16	0.37	-0.21	0.24	0.34	0.05	-0.19	0.29	-0.23	0.19

Multiple Regression Technique - 1978. A stepwise multiple regression analysis (Barr et al., 1976) was performed on the 1978 and 1979 data to formulate a practical and predictive mathematical model for the SOD rate in Lake Erie. Three models were examined to model the 1978 data collected. In the first regression model, all the variables that could possibly affect the SOD rate were entered. From these variables, only those which improved the r^2 (coefficient of determination) a significant amount were chosen for the equation.

The equation for the first model gave an r^2 of 0.68 and a probability of $P = 0.004$, and included five variables: number of benthos (B), percent total volatile solids in the sediment (TVS), total iron and total phosphorus in the sediment (TFeS, TPS) and the bottom temperature (T). The equation was:

$$0.45 \log B + 0.06\ V + 0.003\ TPS + 0.00003\ TFeS + 1.28\ TVS - 4.98 = SOD\ rate.$$

In an attempt to provide a more accurate estimate of the SOD rate, a second model containing an additional discrete variable termed stratification was used. This variable answered either "yes" (1) or "no" (0) to the question of whether or not the water column above the sample site was stratified. This model displayed a coefficient of determination of $r^2 = 0.80$ ($P = 0.0002$) with the variable of stratification (S) most important: the stratified stations would tend to have higher SOD rates. The only other change in the variables chosen for the second predictive equation were the addition of total manganese in the sediments (TMnS) and the withdrawal of the total phosphorus and total volatile solids in the sediment. The bottom temperature (T), log number of benthos (B) and total iron in the sediments (TFeS) remained in the equation. The regression formula chosen for the second model was:

$$\text{SOD rate} = 1.75\ S + 0.002\ \text{TMnS} + 0.004\ \text{TFeS} + 3.37 \log T + 0.88 \log B - 13.25.$$

Since the variable of stratification improved the second model approximately 12 percent, the third model used only those stations whose water columns were stratified to further examine the effect of stratification. The variable, stratification, was dropped from the model since all the stations were considered "stratified." The third model showed an $r^2 = 0.87$ ($P = 0.006$) and contained all new variables in the final equation. These variables were the PHI value of the sediments (0), total solids of the sediment (TS), total phosphorus and DO in the hypolimnion (TP, DO) and the percent of the incident light reaching the sediments (L). The equation chosen was the best five variable model found:

$$\text{SOD rate} = 0.13\ 0 + 0.02\ \text{TS} + 0.01\ \text{TP} - 1.69 \log \text{DO} - 3.07\ L + 2.46.$$

An important fact to remember is since there was no sediment chemistry or grain size analysis performed in the western basin, the three models presented did not include the western basin. However, all correlation coefficients between two variables did include the western basin data, whenever western basin data was available.

1979 Experiments

SOD Rates and WOD Rates. The SOD rates for the four cruises are listed in Table 15. The twenty-four hour WOD rates, along with all other WOD rate measurements appear in Table 16. As previously mentioned, due to the unexplained oxygen production in

TABLE 15

LAKE ERIE SEDIMENT OXYGEN DEMAND RATES FOR 1979

Cruise	Day	Station	Chamber	SOD[1]	Time[2]	DO Hypo[3]	Depth	Temp Hypo[4]
1	167	1	L	0.83	1440	9.05	24.0	8.4
1	167	1	L	1.32	555	9.80	24.0	8.5
1	167	1	L	1.27	2100	9.75	24.0	9.0
1	167	1	D	1.83	2110	9.95	24.0	8.0
1	168	1	L	1.17	5	9.80	24.0	8.5
1	170	2	L	0.97	26	7.40	23.5	10.5
1	170	2	L	0.89	1030	7.20	23.5	10.8
1	170	2	D	2.23	1417	9.10	23.5	9.2
1	170	2	L	0.96	1838	7.25	23.5	10.2
1	170	2	D	1.15	1838	9.10	23.5	9.2
1	171	2	L	1.86	225	8.80	23.5	10.2
1	171	2	D	1.93	138	9.10	23.5	9.2
1	171	2	D	2.50	1044	13.20	23.5	9.0
2	199	1	L	0.95	125	5.15	23.5	9.2
2	199	1	D	1.58	1223	5.20	24.5	8.8
2	199	1	L	0.93	1820	5.00	24.5	9.2
2	200	1	D	1.66	117	6.15	24.5	9.2
2	200	1	L	0.83	1505	5.40	24.0	9.8
2	201	2	L	1.32	740	4.95	23.5	9.8
2	201	2	D	0.55	755	5.10	23.5	9.8
2	201	2	L	1.12	1100	4.45	23.5	9.8
2	201	2	L	0.74	1814	4.40	23.5	9.8
2	201	2	D	0.38	1824	4.65	23.5	9.8
2	202	2	L	0.77	115	4.40	23.5	10.8
2	202	2	L	1.23	830	6.15	23.5	10.8
2	202	2	D	0.22	1205	4.70	23.5	10.5
2	202	2	L	1.10	1440	4.65	23.5	10.5
2	202	2	D	0.30	1525	4.40	23.5	10.5
2	202	2	L	1.30	1150	6.15	23.5	10.8
3	229	1	D	0.47	1130	1.06	24.0	10.5
3	229	1	L	0.83	1135	1.30	24.0	10.5
3	229	1	L	0.81	2055	2.10	24.0	11.5
3	230	1	L	1.61	930	1.70	24.0	8.1
3	230	1	L	0.41	1115	1.70	24.0	8.1
3	230	1	L	0.97	1425	1.86	24.0	11.5
3	231	2	L	0.38	2020	1.08	23.8	11.5
3	231	2	D	0.34	2000	1.22	23.8	11.5
3	231	2	D	0.27	858	0.96	23.8	11.5
3	231	2	L	0.61	858	1.53	23.8	11.5
3	231	2	D	0.19	1340	1.40	23.8	11.5
3	232	2	D	0.47	735	1.51	23.8	11.5

TABLE 15 CONTINUED

LAKE ERIE SEDIMENT OXYGEN DEMAND RATES FOR 1979

Cruise	Day	Station	Chamber	SOD[1]	Time[2]	DO Hypo[3]	Depth	Temp Hypo[4]
3	232	2	L	0.52	255	1.51	23.8	11.5
3	232	2	L	0.38	1140	1.06	23.8	11.5
3	232	2	D	0.19	1149	0.84	23.8	11.5
3	232	2	L	0.49	735	1.60	23.8	11.5
3	233	1	D	0.73	900	1.27	24.0	10.5
3	233	1	D	0.10	1550	1.30	24.0	10.5
3	233	1	L	0.24	2030	0.98	24.0	14.5
3	233	1	D	0.13	2035	0.58	24.0	11.5
3	233	1	L	0.31	910	2.00	24.0	11.5
3	234	1	D	0.17	1325	1.68	24.0	11.5
4	272	1	L	1.07	1452	5.25	24.1	16.8
4	273	1	L	0.94	910	5.20	24.1	17.5
4	274	2	L	0.84	1815	4.50	23.8	18.7
4	274	2	L	0.61	1420	4.30	23.8	18.8

---

[1] Sediment oxygen rate in $g0_2/m^2$/day.

[2] Starting time of the SOD measurement.

[3] Average hypolimnetic DO in mg/l.

[4] Average hypolimnetic temperature in °C.

TABLE 16
RESULTS OF HYPOLIMNETIC WATER OXYGEN DEMAND MEASUREMENTS (mg l^{-1})

Station A-1

	Cruise 1	Cruise 2	Cruise 3	Cruise 4
Light Bottle (day)	-0.05±0.12	0.19±0.25	0.07±0.09	0.03±0.06
Dark Bottle (day)	0.16±0.06	0.24±0.06	0.09±0.10	0.04±0.05
Gross Productivity (day)	0.21±0.13	0.05±0.25	0.02±0.13	0.01±0.08
Dark Bottle (night)	-0.18±0.03	0.04±0.11	0.10±0.20	1.52±0.02
Light Bottle (24 hours)	Lost	0.07±0.06	0.20±0.08	0.01±0.05

Station A-2

	Cruise 1	Cruise 2	Cruise 3	Cruise 4
Light Bottle (day)	-0.07±0.04	0.10±0.05	0.13±0.09	0.06±0.06
Dark Bottle (day)	-0.04±0.06	0.15±0.08	0.19±0.12	0.03±0.01
Gross Productivity (day)	0.03±0.07	0.05±0.09	0.06±0.11	NONE
Dark Bottle (night)	-0.01±0.05	-0.09±0.09	-0.09±0.10	-0.03±0.05
Light Bottle (24 hours)	0.08±0.05	0.12±0.04	0.32±0.04	0.13±0.04

Cruise Dates
1. June 15-21, 1979
2. July 18-23, 1979
3. August 16-22, 1979
4. September 29-October 2, 1979

Note: Positive value indicates oxygen consumption.

the dark WOD bottles, the twenty-four hour light bottle WOD rates were used in the calculations for this investigation.

Relationship of Variables by Cruise. Cruises one, two and three were conducted in 1979 during stratified conditions in the central basin while cruise four was during a period of destratification. Since the partial circulation of the basin's waters during the last cruise was inconsistent with the sampling conditions of the three previous cruises, only the correlation coefficients comparing the stratified periods will be presented. In addition, only a limited number of observations were made during cruise four which may not be representative of the true conditions.

The mean hypolimnetic cruise values for the parameter are listed in Table 17.

The hypolimnetic DO, aerobic heterotrophic bacteria, and the SOD rate decreased throughout the period of stratification while the temperature, WOD rate, hypolimnion thickness, nitrate/nitrite, log corrected chlorophyll a and the log phaeophytin pigment increased during the same period. The correlation coefficients and probabilities for each of these hypolimnetic variables with the cruise appear in Table 18.

Variables Correlated with the SOD Rate, and with the Hypolimnetic Oxygen Concentration. Some variable correlations with the SOD rate include the cruise or day sampled (r = -0.69, P = 0.0001), the time the SOD rate was measured (r = -0.30, P = 0.04), DO (r = 0.77, P = 0.0001), temperature (r = -0.62, P = 0.0001), WOD rate (r = -0.61, P = 0.0001), log of corrected chlorophyll a (r = -0.64, P = 0.0001) and the log of the pheophytin pigment (r = -0.36, P = 0.03). These correlations with the SOD rate appear in Table 19.

TABLE 17

HYPOLIMNETIC VARIABLE MEANS FOR EACH CRUISE - 1979

Variable	Cruise 1	Cruise 2	Cruise 3	Cruise 4
Number Samples	13.00	16.00	22.00	4.00
Day (Julian)	169.00	201.00	231.00	273.00
SOD ($g0_2/m^2/d$)	1.45	0.94	0.48	0.87
WOD ($g0_2/m^3/d$)	0.08	0.10	0.25	0.07
DO (mg/l)	9.20	5.06	1.37	4.81
Temperature (°C)	9.30	9.90	11.10	17.95
Hypo. Thickness[1] (m)	3.70	4.30	4.70	23.95
Conductivity (umho/cm)	182.00	197.00	205.00	242.00
pH (S.U.)	8.10	8.20	7.80	7.90
Alkalinity (P)[2]	0.09	0.54	0.37	0.00
Alkalinity (T)[2]	97.00	93.60	93.80	95.60
Phosphorus (T)	15.20	25.80	20.00	21.00
Phosphorus (TD)[3]	15.76	12.66	8.67	17.37
Phosphorus (SR)[4]	2.16	3.49	2.84	8.35
Chlorophyll a (ug/l)	1.29	2.55	4.71	1.58
Pheophytin (ug/l)	0.55	0.61	1.88	1.09
TSS (mg/l)	2.47	2.40	5.28	2.16
RS[5] (mg/l)	1.12	1.04	3.58	1.08
TVS (mg/l)	1.35	1.37	1.70	1.08
NO_3+NO_2 as N (ug/l)	139.00	252.00	336.00	95.20
NH_3 as N (ug/l)	44.00	32.80	14.90	88.40

[1] Hypolimnion was destratifying. This value represents the depth of the water column.

[2] Phenolphthalin and total alkalinity (mg/l as $CaC0_3$)

[3] Total dissolved phosphorus (ug/l)

[4] Soluble reactive phosphorus (ug/l)

[5] Residual solids

TABLE 18

CORRELATION COEFFICIENTS BETWEEN HYPOLIMNETIC VARIABLES AND THE CRUISE FOR 1979

Variable	r	P	n
SOD	-0.68	0.0001	51
DO	-0.96	0.0001	51
WOD	0.82*	0.0001	46
Temperature	0.62	0.0001	51
Hypolimnion Depth	0.36	0.009	51
Chlorophyll a	0.51	0.0001	51
Pheophytin	0.36	0.008	51
NO_3/NO_2-N	0.87	0.0001	51
Chlorophyll a (log)	0.70	0.0001	51
Pheophytin (log)	0.64	0.0001	51

*The mean WOD and SOD rates were used to obtain the correlation coefficient and are not conclusive.

n = number of observations
r = correlation coefficient
p = significance probability of the F-values

TABLE 19

HYPOLIMNETIC VARIABLES CORRELATED WITH THE SOD RATE - 1979

Variable	r	P	n
Day	-0.69	0.0001	46
Time	-0.30	0.04	46
Hypolimnetic DO	0.77	0.0001	46
Temperature	-0.62	0.0001	46
WOD	-0.61*	0.0001	7
Chlorophyll a	-0.64	0.0001	38
Pheophytin	-0.36	0.03	38
NO_3/NO_2-N	-0.48	0.003	36

*The mean WOD and SOD rates were used to obtain the correlation coefficient and are not conclusive.

n = number of observations
r = correlation coefficient
p = significance probability of the F-values

Relationship Between the SOD rate, WOD rate and Hypolimnetic Oxygen Depletion in the Central Basin. Table 20 shows the relationship of the SOD and WOD rates throughout the four cruises. The volumetric units were used for comparison to take into account the variations in the hypolimnion thickness. In cruise four (September to October), the central basin was destratifying with an undefined hypolimion; therefore, the depth of the lake at these points (24.1 m at A-1 and 23.8 m at A-2) was used for the hypolimion thickness in the calculation of the volumetric SOD rate. The total oxygen demand rate (TOD rate) is the sum of the volumetric WOD and SOD rates.

In cruise one, station A-1, the WOD bottles were lost so the twenty-four hour WOD and TOD rates could not be calculated. The mean volumetric TOD rates for each cruise were 0.43, 0.33, 0.35 and 0.11 g $O_2m^{-3}d^{-1}$ (Table 20) and the mean rate for the stratified period (cruise one to three) was 0.36 g $O_2m^{-3}d^{-1}$. There was no significant correlation of the TOD rate to the cruise. Using the value of 0.36 g $O_2m^{-3}d^{-1}$ to represent the TOD rate of the stratified period, the monthly hypolimnetic oxygen depletion rate (30 day TOD) would be 10.8 mg $O_2l^{-1}mo^{-1}$ for an average hypolimion thickness of 4.35 meters!

The percentage of the TOD rate contributed by the SOD rate for each of the four cruises was 81.0, 69.5, 28.5 and 54.5 percent (Table 20). Although the entire water column depth was used in the calculations for cruise four, the extremely low WOD rate at station A-1 (0.01 g $O_2m^{-3}d^{-1}$) accounts for the relatively high contribution by the SOD rate to the TOD rate. The TOD rate remained relatively constant because as the SOD rate dropped, the WOD rate increased during the first three cruises (Table 20).

TABLE 20

COMPONENTS OF THE HYPOLIMNETIC OXYGEN DEMAND IN CENTRAL LAKE ERIE - 1979

Station:	A-1				A-2			
Cruise:	1	2	3	4	1	2	3	4
SODa	1.28	1.19	0.56	1.01	1.56	0.82	0.38	0.73
SODv	0.51	0.19	0.10	0.04	0.35	0.23	0.10	0.03
WODa	---	0.43	1.10	0.24	0.36	0.42	1.22	3.09
WODv	---	0.07	0.20	0.01	0.08	0.12	0.32	0.13
TODv	---	0.26	0.30	0.05	0.43	0.35	0.42	0.16
TOD (%SOD)	---	73	33	80	81	66	24	19
TOD (%WOD)	---	27	67	20	19	34	76	81
Hypo (m)	2.5	6.2	5.5	24.1	4.5	3.5	3.8	23.8

areal = g O_2/m^2/day
volumetric = g O_2/m^3/day
Hypo = hypolimnion thickness (meters)

SOD = sediment oxygen demand
WOD = water oxygen demand
TOD = total oxygen demand

Multiple Regression Technique

Only a select number of variables were entered into the regression model so that misleading results would not appear. For example, although the hypolimnetic temperature is strongly correlated with the SOD rate ($r = -0.62$, $P = 0.0001$), this doesn't necessarily mean that the temperature influenced the SOD rate in this set of data. Other relationships could cause the SOD rate and temperature to be correlated such as the day sampled. The SOD rate drops throughout the summer ($r = -0.69$, $P = 0.0001$) while the hypolimnetic temperature rises ($r = 0.64$, $P = 0.0001$); however, the rise in temperature is ony from 9 to 11°C during this period, which would not likely affect the SOD rate. It also seems unlikely that this would account for 38 percent ($r^2 = 0.38$) of the variability in the SOD rate as suggested by the correlation between the SOD rate and temperature and the regression models when the temperature was included. This is particularly true when the relationship between the temperature and SOD rate is inverse. Caution must be used when deciding which variables are to be entered into the regression model to prevent misleading results.

After several regression models were tried, the following parameters were included in the final model. These included the DO, total and phenolphthaline alkalinity, log of corrected chlorophyll a and pheophytin pigments, total suspended and volatile solids in the sediment, nitrate + nitrite, total ammonia, total phosphorus in the sediment and the time of day sampled. The stepwise multiple regression model chosen for 1979 was:

$$050 \log DO - 0.27 \log chl\ \underline{a} - 0.04\ TSS + 0.38\ TVS - 0.0001\ H - 0.22 = SOD\ rate$$

where DO = hypo DO

Chla = corrected chlorophyll a

TSS = total suspended solids (sediment)

TVS = total volatile solids (sediment)

H = the time of day

The coefficient of determination for this model is $r^2 = 0.70$ ($P = 0.0001$) and the degrees of freedom are 33.

DISCUSSION

Historical SOD Rates Compared With Values from Present Study

Other researchers who have conducted research studies on the SOD of Lake Erie include Blanton and Winklhofer (1971), Lasenby (1979), Leutheuser (1981), Lucas and Thomas (1971) and Snodgrass and Fay (1980).

Lucas and Thomas (1971) measured the *in-situ* SOD rates at five central basin stations in 1970. The methodology and chambers used by Lucas and Thomas are identical to that in this investigation. Their mean SOD rates for undisturbed sediments in mid-June, early August and early September were 1.45, 0.43 and 1.3 g $O_2m^{-2}d^{-1}$. In August, the daytime rates were all 0 g $O_2m^{-2}d^{-1}$ and at night the SOD rate averaged 0.7 g $O_2m^{-2}d^{-1}$ giving a daily integrated rate (mean of August SOD rates) of 0.43 g $O_2m^{-2}d^{-1}$. Lucas and Thomas believed that the reason the SOD rates were zero during the daylight hours was due to algal photosynthesis, either in the water column or at the sediment surface, producing enough oxygen to off-set the SOD rate. In our studies, we found no significant difference between the SOD rates at night and day, as was the case with the rates from the light and dark chambers.

Blanton and Winklhofer (1971) also conducted *in-situ* SOD rate measurements in Lake Erie's central basin using a rectangular box. SOD rates were determined during late July and early August of 1970 and their mean SOD rate for that period was 0.32 g $O_2m^{-2}d^{-1}$, quite comparable to the 0.4 g $O_2m^{-2}d^{-1}$ SOD rate of Lucas and Thomas (1971).

Lasenby (1979) incubated mud cores to determine the laboratory SOD rates from May to September of 1978. The mean SOD rate for the summer was 0.43 g $0_2m^{-2}d^{-1}$, and the mean rates for each month appear in Table 21.

These values are quite similar to the mean summer rate reported by Snodgrass and Fay (1980). The rates for June and September are much lower than those found by Lucas and Thomas but agree fairly well with the August rates of Snodgrass and Fay (1980), Lucas and Thomas (1971) and Blanton and Winklhofer (1971).

Snodgrass and Fay (1980) measured the SOD rates at stations A-1 and A-2 in the central basin from June to August in 1979 as was done in the present investigation, but they used a hemispherical chamber. At station A-1 their mean SOD rate for the stratified period was 0.3 g $0_2m^{-2}d^{-1}$ and at station A-2 it was 0.4 g $O_2m^{-2}d^{-1}$ with the rate decreasing throughout the summer period. Both of these two rates compare favorably with the previous late summer measurements, but not with the mean of the entire summer period. A value for the mean summer SOD rate of 0.35 g $0_2m^{-2}d^{-1}$ implies that a larger rate in early summer and lower rates in late summer occurred since we know the rate decreased with time. As a result, a mean summer SOD rate of 0.35 g $0_2m^{-2}d^{-1}$ could significantly underestimate the SOD rates obtained by Blanton and Winklhofer (1971) and Lucas and Thomas (1971) in late summer.

The difference between the SOD rates recorded by different researchers have been commonly attributed to annual ambient changes in the variables measured. However, upon closer examination of the Lake Erie SOD rates and the methodology used to obtain these rates, it seems possible that the SOD rate for the lake is a relatively constant value compared with the annual fluctuations of the various biological and chemical constituents.

TABLE 21

CENTRAL BASIN SOD RATES (g $O_2m^{-2}d^{-1}$) OF SEVERAL INVESTIGATORS

	June	July	August	Sept.
Present study (1979)	1.45±0.55	0.94±0.43	0.48±0.24	0.87±0.19
Lucas & Thomas (1971)	1.45 (1.60*)	---	0.43	1.30
Blanton and Winklhofer (1971)	---	---	0.32	---
Snodgrass & Fay (1979)	mean summer rate of 0.35			
Lasenby (1979)	0.44	---	0.27	0.32

*A June mean value of 1.6 g $O_2m^{-2}d^{-1}$ was reported by Lucas and Thomas in which they included several observations when the sediments within the chamber were slightly to moderately resuspended.

In comparing the results just presented with those of this report we find that the rates of Lucas and Thomas (1971), Blanton and Winklhofer (1971), Lasenby (1979) and Snodgrass and Fay (1980) all agree fairly well with those presented in this paper.

In Table 21, the June values for this study are identical to those measured by Lucas and Thomas (1971) when the sediments were not disturbed. Including Blanton and Winklhofer's (1971) results in this comparison, the August SOD rates are also very similar; however, the results of Lasenby (1979) are consistently lower than those for the other investigations. These lower SOD rates are suspected to be due to the use of sediment cores to measure the SOD rate. The collection of cores may result in disturbing the structure of the sediments, thus giving artificial results. In addition, Lasenby stirred the water above the sediment in his investigation only at the beginning and end of the incubation period. As Rybak (1966) pointed out, if the overlying water is not circulated as it is in its natural environment, artificial microstratification results immediately above the sediments giving lower oxygen consumption values. Since Lasenby (1979) measured the DO in the sediment column at the same time the mixing took place, we have no insight into the mechanism of the oxygen depletion within the column. It can only be assumed that Lasenby's results are lower than the ambient SOD rate.

The most probable reason that the SOD rates of Snodgrass and Fay (1980) also appear consistently lower is due to the poor circulation of the water within the chamber, similar to the consequences encountered by Lasenby's sediment cores. Fay (personal communication) found that it took six minutes for the water in the hemispherical chamber to be mixed when a rhodamine dye solution was injected into it. In the chamber used by Lucas and Thomas (1971) and this study, the circulation time was approximately 22 seconds with an average velocity of 5 to 5.5 cm/sec. The centralized location of the circulation system guaranteed complete mixing. Snodgrass and Fay's hemispherical chamber contained a stirring device attached to the top of the chamber which left the water directly overlying the sediments (1-5 cm) poorly mixed, if at all. The average current velocity produced in their chamber was about 2 cm/sec (2.5 times less than the chamber used in this study) and was most likely well below that figure at the sediment-water interface since the stirring device was at the top of the hemisphere. In addition, the average bottom current at those stations was approximately 4-5 cm/sec (Blanton and Winklhofer 1972), much greater than the currents in the hemisphere.

From the information presented, it seems reasonable to assume that the water currents directly above the sediments do indeed play a significant role in determining the SOD rate. The most probable process responsible for this is the microstratification of the overlying waters when not circulated as described by Rybak (1966), Brundin (1951), Graneli (1978), and Milbrink (1969), which greatly decreases the diffusion of oxygen through the sediments, limiting both the biological and chemical oxygen demands (Boynton et al. 1981).

Seasonal Relationship of the SOD Rate, WOD Rate and the Hypolimnetic Oxygen Demand. During the summer stratification of Lake Erie's central basin, the DO is gradually depleted due to various oxygen consuming processes throughout the water column and in the sediments. During 1970, the oxygen produced by photosynthesizing algae was not enough to affect the net DO content in the hypolimnion (Burns and Ross 1972c); however, during the same period of time approximately 12% of the oxygen consumed in the central basin hypolimnion was supplied by oxygen exchange processes with the mesolimnion (Burns 1976). Also, it is suspected that oxygen-rich western basin water can be entrained near the boundary with the central basin and brought into the central basin (Herdendorf, personal communication), although values for this transfer would most likely be insignificant. The possibility that oxygen is transferred from the cold and well oxygenated eastern basin hypolimnion to the hypolimnion of the central basin during the late summer was substantiated by Boyce et al. (1980). During the summer of 1977 Boyce et al. (1980) found that approximately 25-50 percent of the central basin hypolimnetic oxygen demand could be met by the oxygen transfer from the eastern basin. Using figures for the hypolimnetic deficit rates from Charlton (1979), Boyce et. al (1980) calculated that the oxygen depletion in the central basin could be slowed 5 to 10 days by this entrainment. It is apparent, however, that the oxygen supply from algal production, mesolimnion transfer, plus eastern basin and western basin entrainment was not enough to prevent severe oxygen depletion, hence the decline of oxygen throughout the summer.

As previously mentioned, the mean TOD rate for the central basin area sampled in 1979 was 0.36 g $O_2m^{-3}d^{-1}$ or 10.8 mg $O_2l^{-1}mo^{-1}$. This value assumes an average hypolimnion thickness of 4.35 meters (found in this study) and indicates that if the central basin hypolimnion were a closed system, the oxygen would be depleted within a few weeks. It would appear that a sufficient oxygen supply from outside the central basin hypolimnion prevented the immediate and severe oxygen depletion from the WOD and SOD.

This extremely important issue defines the difference between the cruise interval technique (Burns 1980) and the in-situ oxygen demand technique demonstrated in this paper. The cruise interval technique measures the oxygen concentration in the hypolimnion during several cruises throughout the year. The cruise interval hypolimnetic oxygen depletion rate is measured as the difference between the DO concentrations over a specified period and adjusted for the hypolimnion thickness. This is a survey technique and only gives information as to how much oxygen is depleted overall from the hypolimnion. Table 15 uses the data from Table 16 to calculate the cruise interval rate for this study (which averages 0.126 g $0_2/m^3$/day or mg O_2/l/day). Figure 17 presents cruise interval rates measured in the central basin from 1970 to 1980. The oxygen depletion rate remains fairly constant throughout stratification as was shown in this study. The cruise interval technique yields values less than half of the oxygen depeletion rates found using the in-situ oxygen demand technique, primarily due to the fact that these two techniques are qualitatively different. The cruise interval technique measures the overall oxygen depletion rate while the in-situ methods measure the components of the depletion rate. Therefore, the results from these two measurements should not be seriously compared as to which best expresses the hypolimnetic oxygen depletion rate. The cruise interval technique, of course, gives an excellent estimate of the overall deficit rate while the in-situ oxygen demand measurements describe quite accurately the natural components of the oxygen depletion. This accounts for the discrepancies between the cruise interval technique and the in-situ oxygen demand technique discussed by Burns (1980).

A closer look at the components of the in-situ oxygen demand measurements made in 1979 (Table 20) shows that the WOD rate increases throughout stratification ($r = 0.82$, $P = 0.0001$) (Figure 18). The WOD rate for cruises one and two were fairly close (0.7 to 0.12 g $O_2m^{-3}d^{-1}$) but the WOD rate for cruise three increased two to three times (0.20 to 0.32 g $O_2m^{-3}d^{-1}$). This rise in the WOD rate is reflected by the high amount of pheophytin pigment, which is approximately three times higher in cruise three than in cruises one and two (Table 19). The pheophytin concentration represents the algae which have lost their photosynthetic capacity and are dying, which ultimately increases the

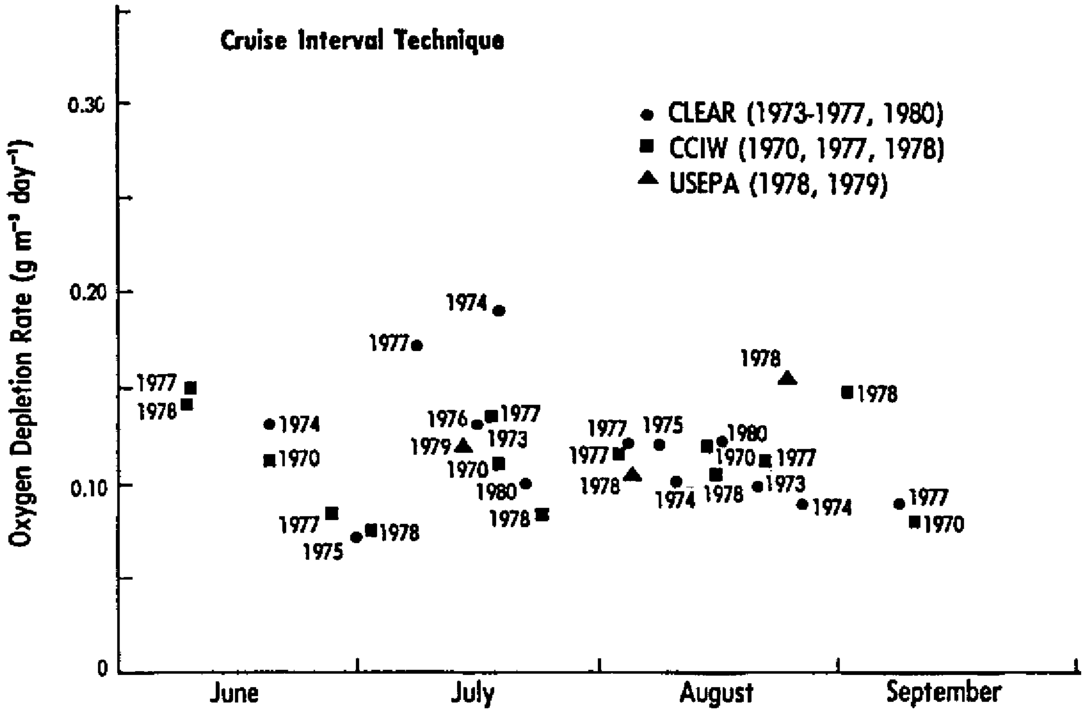

Figure 17. Hypolimnetic Oxygen Depletion Rate in the Central Basin of Lake Erie, 1970-1980.

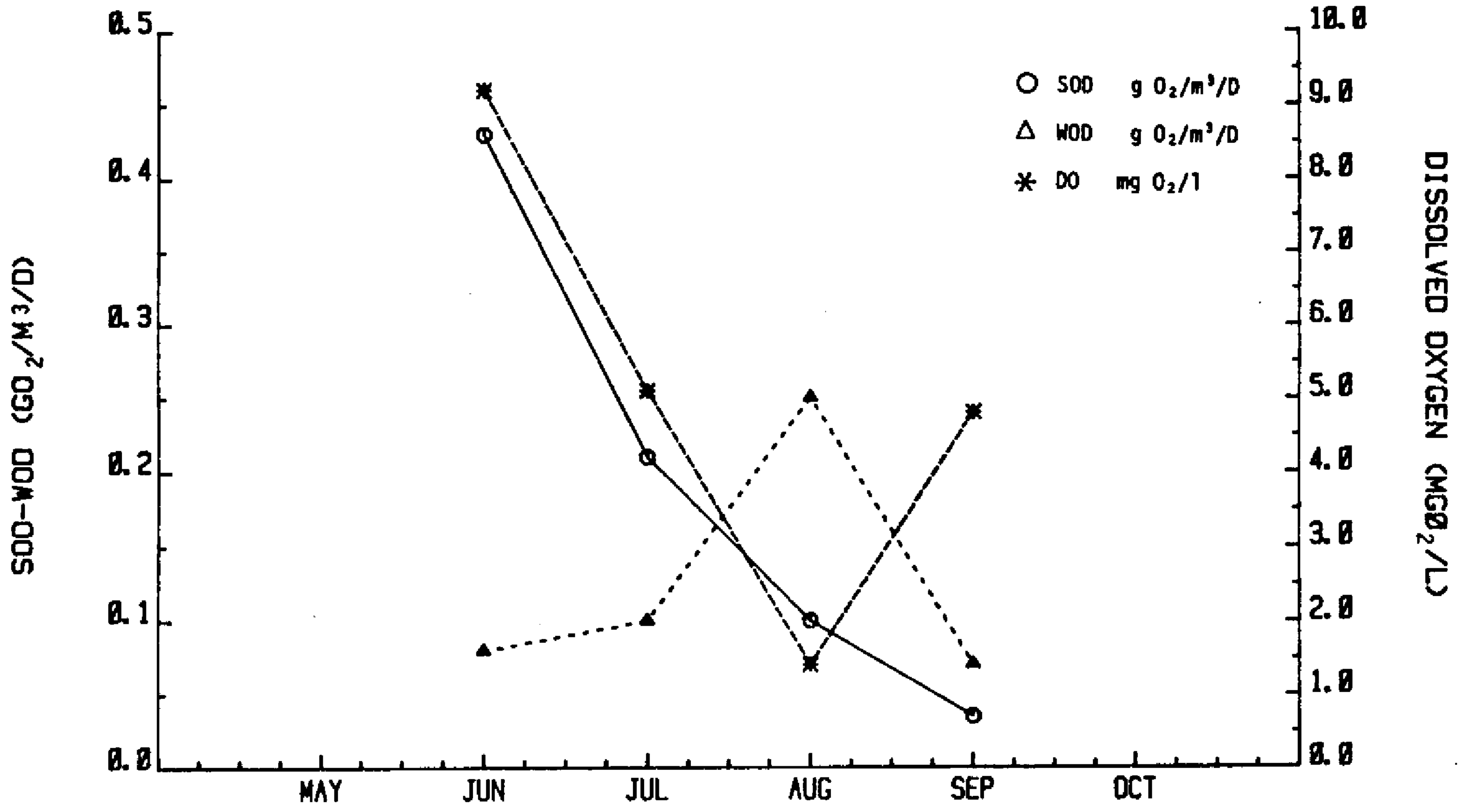

Figure 18. Hypolimnetic Oxygen Depletion Rate in the Central Basin of Lake Erie in 1979

WOD rate through respiration and decomposition. The influence of this decomposition is noted with a correlation coefficient of $r = 0.59$ ($P = 0.0001$) between the WOD rate and pheophytin pigment.

The amount of algal decomposition occurring in the water column is also reflected by the rise in the nitrate plus nitrite concentration during the summer. The WOD rate is correlated with the nitrate and nitrite concentration ($r = 0.53$, $P = 0.0002$) since the nitrate and nitrite concentration reflects the amount of algal decomposition by nitrifying bacteria which releases the nitrate into the water directly above the sediments (Burns and Ross 1972a).

The increase of the WOD rate from June to August is accompanied by a decrease in the SOD rate (Figure 18). The SOD rates fall very low in cruise three due to the low DO concentrations which decreases the diffusion of oxygen through the boundary layer and sediments as well as slowing the diffusion of reduced materials in the sediments to the oxidized microzone at the sediment surface. Also, at DO concentrations below 2-3 mg O_2/l, the benthos consume less oxygen (Berg and Jonasson 1965; Davisen 1931) and at concentrations of 0.5 mg O_2/l and below, bacteria gradually switch from aerobic respiration to fermentation decreasing their oxygen consumption (Zobell 1943). All of the factors associated with low DO concentrations will contribute to the decrease in the SOD rate in cruise three.

The decrease in the SOD rate between cruises one and two, however, was not likely due to the difference in the DO concentration since the DO dropped from 9.19 to 5.09 mg O_2/l, which is not low enough to significantly affect diffusion or respiration rates. In addition, when using a DO correction formula for SOD rates developed by Butts (1981), the rates are still quite different meaning that factors other than the DO concentrations are affecting the SOD rates between cruises one and two. To explain the lower SOD rates in cruise two we looked at changes in the concentrations of parameters measured during the two cruises. The only noticeable change was in the corrected chlorophyll a concentration which increased 100 percent, and under the right conditions could have photosynthetically produced enough oxygen to offset the SOD rate. However, we have no data to substantiate this theory.

Relationship of SOD Rate with Variables

Temperature. In 1978, the effect of temperature on the SOD rate is relatively clear. The temperature-corrected SOD rates showed no difference between the mean values for each basin while the rates at their ambient temperatures showed a significant difference between the mean SOD rates for the western basin and the rates for the central and eastern basin.

A temperature correction coefficient of 1.047 which is used for carbonaceous BOD determinations was used in this study. To employ this coefficient it must be assumed that the entire oxygen uptake is due to carbonaceous demands. Mathis and Butts (1981) found that a correction coefficient of 1.085 accounted for both the carbonaceous and nitrogenous demands in natural waterways. However, in this investigation when the coefficient of 1.085 was used for the SOD_{10} rate, it was correlated with the same parameters as the SOD_{10} rate using the coefficient of 1.047, with the exception of one variable. While the SOD_{10} rate used here was not correlated with the temperature, the SOD_{10} rate using the coefficient of 1.085 showed a correlation of $r = -0.50$ ($P = 0.004$) with the temperature. From this information it can be seen that the coefficient of 1.047 could be applied much better than the coefficient of 1.085.

For the 1979 data, a negative correlation of r = -0.62 (P = 0.0001) exists between the SOD rate and the temperature. However, this is due to the fact that the hypolimnetic temperature rises during the summer while the SOD rate drops. It must be pointed out that the temperature only rises 4°C which would not likely affect the SOD rate, particularly with an inverse relationship between these two variables. In other words, the correlation between the SOD rate and the temperature in 1979 is due to their respective correlations with the cruise, not because the temperature affects the SOD rate over a 4°C range.

DO and Cruise. The SOD rate was negatively correlated with the day sampled (r = -0.69, P = 0.0001) in 1979, indicating that the SOD rate decreases as the stratification period (summer) progresses. Perhaps the most definitive relationship encountered in this investigation is between the SOD rate and hypolimnetic DO concentration. When considering the effect of only the DO on the SOD rate (simple regression) the DO concentration can account for approximately 59 percent of the variability found in the SOD rates (r = 0.77, P = 0.0001). As mentioned previously, the DO and SOD rate in 1979 both decrease throughout the summer which raises the question of whether or not the DO concentration becomes a limiting factor to the SOD rate. No insight into this matter was gained from the 1978 measurements since a spatial sampling method was used.

Between cruises one (mid-June) and two (mid-July) in 1979, the hypolimnetic DO concentration dropped 45 percent from 9.19 to 5.09 mg O_2/l while the SOD rate dropped from 1.45   0.55 to 0.94   0.43 g O_2/m^2/day (35 percent). Investigators who did find oxygen concentration to be a limiting factor for the SOD found the critical range to be from 3 mg O_2/l and below (Baity 1938; Bowman and Delfino 1980; Knowles et al. 1962; Pamatmat and Banse 1969; and Walker and Snodgrass 1978).

By cruise three, 1979, (mid-August) the DO concentration did enter this critical range, dropping from 5.09 mg O_2/l to an average of 1.4 mg O_2/l (275 percent) while the SOD rate also continued to drop to a mean rate of 0.48 0.24 g O_2/m^2/day (49 percent). In addition, during cruise three, exponential SOD curves began to appear. These curves exhibited a higher linear correlation with a semi-log relationship than a linear one. However, these exponential curves did not reflect an increase in the SOD rate as seen by the similar values for the slopes of the SOD rate curves when either the linear or the exponential forms were considered. This would imply a flattening of the latter portion of the curve occurred due to the oxygen supply to the sediments being limited by the small amount of oxygen in the overlying waters. Hayes and MacAuley (1959) found the function of the SOD rate and the DO to be linear but they maintain that in almost all of their experiments there is a "well-diminishing rate of O_2 uptake...due to inadequate stirring, or a slowing of uptake as the O_2 tension falls." Similarly, Pamatmat (1971a) found the SOD rate to be a strong function of the oxygen concentration below 1 mg O_2/l and linear above 1 mg O_2/l due to biological processes and Newrkla and Gunatilaka also found lower SOD rates during late summer in oxygen-stressed lakes. When considering chemical exchange processes such as diffusion, the function appears to become second-order with respect to the DO concentration. Walker and Snodgrass (1978) also discovered the possible non-linear functions due to a two-step curve representing oxygen uptake functions below and above 1-2 mg O_2/l. As the oxygen concentration falls, the respiratory mechanism of many aquatic oligochaetes, which comprise the majority of the benthos, slows and oxygen consumption becomes very low (Davisen 1931). In some cases, several oligochaete species have been found to live anaerobically for up to one month (Berg and Jonasson 1965). When community respiration slows, presumably as the oxygen levels drop to 1-2 mg O_2/l, the biological consumption diminishes and the chemical demand becomes prominent, displaying a first- or second-order function with respect to the accumulation of reduced materials in the sediments. The limiting oxygen concentration for bacterial aerobic respiration is about 0.5 mg 0_2/l (ZoBell 1943).

A primary mechanism of oxygen transfer from the water to the sediments is diffusion, particularly in quiescent environments (Lee 1970). Factors such as increased current velocities without physical resuspension of the sediment, bioturbation and physical resuspension of the sediments due to scouring current velocities affect the consumption rate to varying degrees and quite often dominate the oxygen demand (Boynton et al. 1981; Edberg and Hofsten 1973; Edwards 1958; Graneli 1972, 1977; Lee 1970; NCASI 1978; Nichols 1974; and Rybak 1966, 1969).

A very important point which must be considered in all SOD investigations is whether or not the sediment oxygen uptake curve is linear, exponential or logarithmic depends upon the actual natural conditions and will not be the same for all SOD rates.

Benthos. The total number of benthic macroinvertebrates account for 46 percent of the variability in the SOD rate. The oligochaetes, which comprise 86 percent of the number of benthos found, can explain 38 percent of the SOD rate variability (Table 8). The positive correlation between the benthos and the SOD rate is not surprising as many investigators have noted the various effects of the benthos on the chemical exchange rates between the water and sediment (Anderson 1977; Edwards and Rolley 1965; Graneli 1977; Hargrave 1969; Rybak 1969; and Walsh 1948). Teal and Kanwisher (1961) and Smith et al. (1973) found the macroinvertebrates to contribute 40 percent and 20 percent, respectively, to the total SOD through respiration and bioturbation. The benthic activity accounted for an increase in the sediment surface area allowing increased gas exchange between the deeper sediments and water as well as exposing reduced materials to oxidation (Berg et al. 1962; Crook and Bella 1970; Edwards 1958; Rybak 1966; Smith et al. 1973; Teal and Kanwisher 1961; and Walker and Snodgrass 1978).

Sediment Grain Size Distribution. The PHI value of the sediments (PHI, $0 = -\log_2 E$, where E is the diameter of the grain size in mm) was positively correlated with the SOD rate ($r = 0.58$) indicating that the higher PHI values corresponded to the higher SOD rates. In other words, the particles with the smallest diameter, such as the clays and silts, tend to display the highest SOD. This is most likely due to the higher amounts of carbon (TVS) in these sediments which invertebrates and bacteria use as an energy source through decomposition. In particular, the clay and silt fractions were positively correlated with the SOD rate ($r = 0.60$ and $r = 0.49$, respectively) and the sand and gravel fractions were negatively correlated to the SOD ($r = -0.50$ and $r = -0.31$, respectively).

Odum and de la Cruz (1967) and Fenchel (1970) found a similar positive relationship to the particle size of detritus and oxygen uptake. Hargrave (1972c) demonstrated an inverse relationship between the oxygen demand and sediment particle size while experimenting with sand and detrital substrates. Belanger (1979) also found a greater SOD with organic-muck sediments than with sand bottoms, particularly when the sediments were subjected to higher water currents. In addition, Hargrave (1972c) noted greater variability in the SOD rate with mud sediments than found with sand sediments. As Hargrave suggests, this variation may be due to resuspension of the sediments from the small particle size of the mud giving it a lower settling velocity (v_s) than sand. This fact can become quite significant during the placement of the chamber and when considering the rate of flow inside the chamber. The higher percentage of chemical oxidation of the mud sediments could explain the greater variability in the SOD rates, especially with higher bottom water velocities (Belanger 1979).

Total Volatile Solids. The percent TVS in the sediments were positively correlated with the SOD rate ($r = 0.51$, $P = 0.01$) although some researchers found no such correlation in their studies (Anderson 1939; Belanger 1981; Edwards and Rolley 1965; and Hargrave 1969). Hargrave (1972c) studied sediments with low organic content and found a linear relationship between the logarithmic values of the sediment organic content and the SOD rate ($r = 0.91$, $P = 0.05$). This relationship excluded mud samples due to their high variation in SOD rates from resuspension.

Waksman and Hotchkiss (1938), Teal (1962), Rybak (1969) and Liu (1973) also make reference to the influence of the organic content of the sediments on the SOD rate. They found the organic content to be important in affecting the SOD, particularly at low quantities when the majority of the organic matter is readily oxidized such as the carbohydrates. The findings in this study indicate that at moderate quantities of organic content (2-11 percent), the TVS is indeed correlated with the SOD rate, supporting the idea that the sediment organic content may be a limiting factor for the SOD rate.

Percent Incident Light Reaching the Sediments, Chlorophyll a and Time of Day Sampled. Braidech et al. (1971), Butts and Evans (1979), Davis et al. (1981), Hunter et al. (1973), Lucas and Thomas (1971), O'Connell and Thomas (1965), Thomas and O'Connell (1966) and Zapotosky and Herdendorf (1980) have all noted the possible effects of algal photosynthesis which can supply enough oxygen to reduce the SOD rate. In a 1970 study in Lake Erie's central basin, Lucas and Thomas (1971) found that algal photosynthesis offsets the SOD rate by as much as 0.6-0.7 g 0_2 m^{-2} day^{-1}. The percent light reaching the sediment in the deeper stations ranged from 0-0.57 percent of the incident surface light and its correlation with the SOD rate is $r = -0.40$ ($P = 0.05$).

This small quantity of light at the sediment surface (0-0.57 percent) is well below the one percent compensation depth at which photosynthesis is generally believed to be much less than respiration. However, Cole (1979) points out the photosynthesis may occur below this level, particularly for algae which become adapted to low light levels. Kiefer et al. (1972) found a chlorophyll peak in Lake Tahoe between the one percent and 0.1 percent incidence light levels and Anderson (1968) found the same results when studying in the Pacific Ocean. Baker and Brook (1971) and Brook et al. (1971) found metalimnetic chlorophyll a maxima at a depth to which less than 0.1 percent of the incident surface light was detected. In this investigation we found over 45 percent of the light readings at the sediment surface to have 0.1 percent or more of the incident light.

The negative correlation between the SOD rate and light reaching the sediments (r = -0.40) means that the greater the percent incident light reaching the sediment, the less the SOD rate, presumably due to the oxygen produced by benthic and planktonic algal photosynthesis. Since there is a large amount of chlorophyll a (2-5 ug/l) throughout Lake Erie's hypolimnion (Fay 1976; Fay and Rathke 1980; Fay, personal communication), it is quite feasible that when enough light is present significant quantities of oxygen could be produced, reducing the SOD rate. This point may be illustrated by the 1979 corrected chlorophyll a concentrations which increased quite noticeably from cruises one to three (Figure 19) and is reflected by a correlation coefficient of r = 0.51 (P = 0.0001) with the day sampled. In addition, the correlation coefficient between the SOD rate and the corrected chlorophyll a is r = 0.64 (P = 0.0001) showing that as the chlorophyll a increases, the SOD rate decreases. Although the time of day in 1978 showed no apparent effect upon the SOD rate due to the wide distribution of sediment characteristics encountered throughout the lake, the 1979 SOD rate was negatively correlated with the time of day (r = -0.30, P = 0.04). This means that the highest SOD rates occurred before sunrise. The

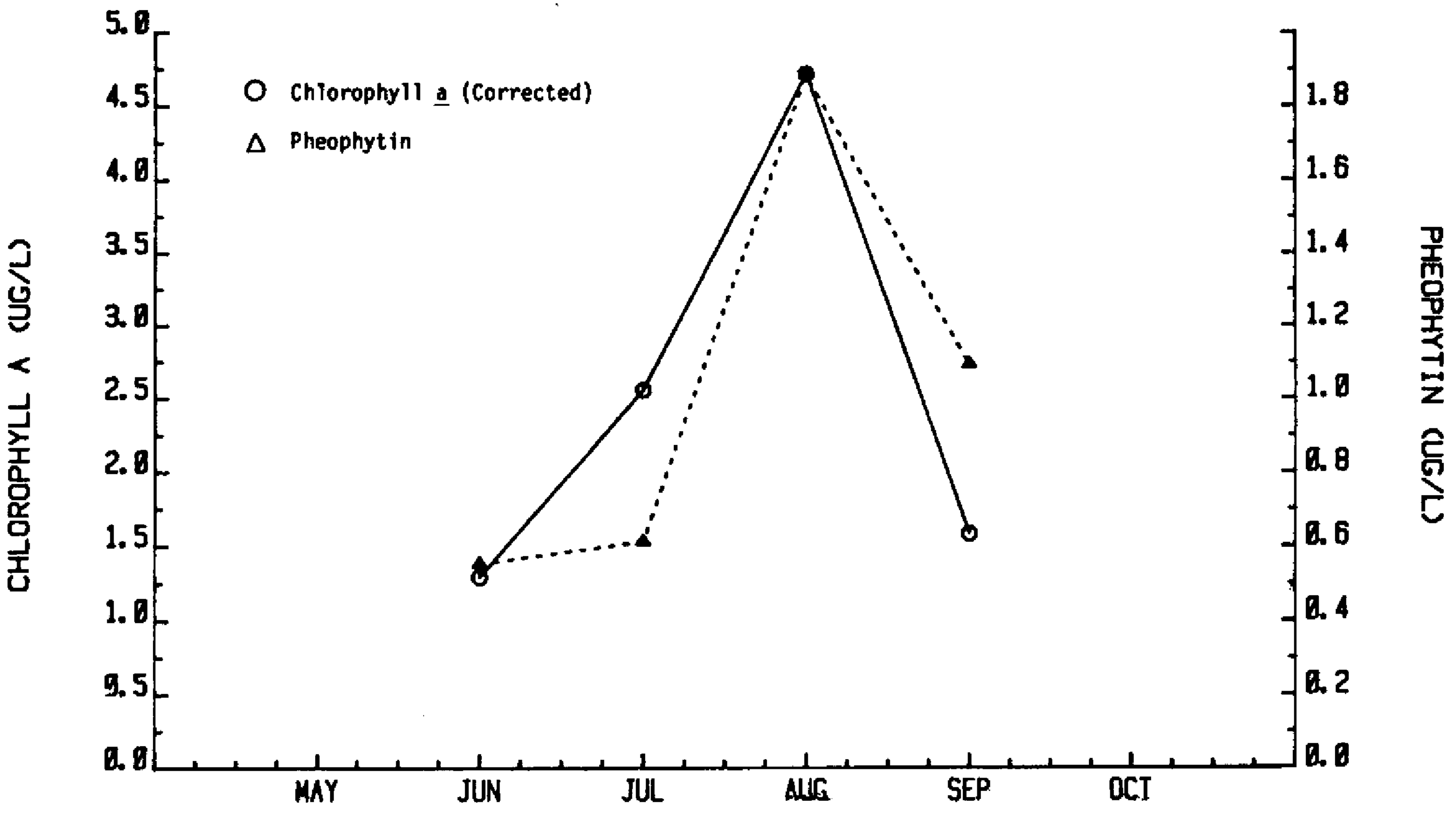

Figure 19. Chlorophyll Pigments in the Central Basin of Lake Erie During 1979

SOD rates were measured from 0000 hours (midnight) to 1845 hours (6:45 p.m.), a few hours before sunset, at approximately six-hour intervals.

This information presented does not conclusively show that the SOD rates are offset by algal photosynthesis or that the SOD rate has a diurnal relationship, but it does demonstrate that these relationships are possible in Lake Erie's central basin.

SOD Chambers. Using a one-way analysis of variance test (ANOVA), no significant difference ($\alpha = 0.50$) was found to exist between the mean SOD rates for the two types of chambers. If photosynthesis does affect the SOD rates, one would expect a difference to be found in the SOD rates measured in the light and dark chambers. This was not the case, possibly due to the fact that the inherent variation of the SOD rate is much greater than that due to photosynthesis. Thus, it appears that the technique of using light and dark chambers placed in-situ is not sensitive enough to detect the often subtle differences in the SOD rate due to photosynthesis over short periods of time.

Inorganic Chemicals in the Sediments. The SOD rate in 1978 is also correlated with the total phosphorus, manganese and iron in the sediments most likely due to the oxidation of these inorganic species during placement of the SOD chamber and possibly by undetected disturbances throughout the experiments. Another possibility could be that these chemicals underwent oxic regeneration from the sediments throughout the summer in large quantities; however, if sufficient quantities could be regenerated they would not react with enough oxygen to noticeably affect the oxygen uptake rate during normal oxygenated conditions (Burns and Nriago 1976; Burns and Ross 1972c). Also, Adams et al. (1982) reported that at central basin station A1 during measurements in summer and fall of 1979, total iron and manganese in the sediments had accounted for less than 1% of the SOD, while ammonia and methane accounted for almost 30% of the oxygen demand.

If the inorganic chemicals in the sediments are released in massive quantities during placement of the chamber and are not fully oxidized throughout the measurement, then the SOD rates obtained may slightly overestimate the actual demand of the sediments under natural conditions. However, it's most likely that the inorganic chemicals in the sediments are exposed and released not only by the placement of the SOD chamber, but by the water flow at the sediment-water interface. The total solids content of the sediments ranges from 23 to 74 percent with a mean value of 51 percent, reflecting the natural resuspension of the sediments, possibly causing the correlation between the inorganic chemicals in the sediments with the SOD rate.

However, to guarantee that the resuspension of the sediments during chamber placement doesn't affect the SOD rate to a significant degree, a period of at least 30 minutes before the SOD rate is taken and after the chamber is on the sediments is recommended.

Heterotrophic Bacteria. The number of aerobic heterotrophic bacteria in the sediments during 1978 and 1979 sampling has been found not to be correlated with the SOD rate but the bacteria in the water directly above the sediments shows a correlation of $r = 0.60$ ($P = 0.0001$) with the SOD rate. It must be remembered that the methodology for the testing of bacteria is far from standard and the results presented here may not represent the actual conditions.

It has been well documented that bacterial communities can greatly contribute to the SOD and that increased bacterial populations will lead to an increase in the SOD rate by directly and indirectly oxidizing reduced chemical species (Hargrave 1969; Hayes and MacAuley 1959; Rao and Burnison 1976; Smith et al. 1972; ZoBell 1946; and ZoBell and Brown 1944).

During the study the mean number of bacteria was found to be greater in the eastern basin and an ANOVA test (P = 0.05) showed it to be significantly different from that of the central basin during 1978. The possibility that the higher SOD rates at the stations sampled in the eastern basin, although not significantly different from the central basin, is influenced by the quantities of heterotrophic bacteria is supported by the observations of Rao and Jurkovic (1979) during their 1978 studies of the Lake Erie sediments. The observed relationship between the SOD rate and bacteria in 1979 is supported by Menon et al. (1972) who noted that the bacterial populations of the waters directly above the sediments were magnitudes higher than that in the overlying waters which lead Rao and Jurkovic (1979) to suggest that the bacterial oxygen uptake (respiration of the bacteria including resultant oxidation of reduced materials) in Lake Erie's hypolimnion could account for the significant oxygen depletion during late summer. Kusnetzov (1935) and ZoBell (1940) concluded that heterotrophic bacterial oxygen consumption significantly affected the oxygen depletion in stratified lakes. Other investigators have also determined that the bacterial decomposition of dead sedimented algal cells largely contributed to the oxygen depletion in Lake Erie's central basin hypolimnion (Burns and Rosa 1980; Burns and Ross 1972b; Lucas and Thomas 1971; and Rao and Burnison 1976). Therefore, it is reasonable to imply that the quantity of aerobic heterotrophic bacteria in the lake may influence the SOD rate throughout the summer.

Nitrate plus Nitrite, Ammonia and Conductivity. The nitrate and nitrite rises considerably during the summer (r = 0.87, P = 0.0001) and is negatively correlated with the SOD rate (r = -0.48, P = 0.003). This relationship is most likely due to the fact that both of these variables are strongly correlated with the cruise. An increase in the NO_3+NO_2 wouldn't reflect the SOD rate as greatly as it does the WOD rate.

This same principle is applied toward the variables of ammonia and conductivity: the correlation of these variables with the cruise is much stronger than with the SOD rate. In addition the small changes in the amounts of the ammonia and conductivity could not possibly have a significant effect upon the SOD rate.

Correlations Between the TVS, TSS and Sediment Grain Size

Presented in Table 8 are correlations between the TVS, TS and the grain size of the sediments. The PHI value of the sediments can explain 59 percent (r^2) of the variability in the TVS. This supports Hargrave's (1972c) view that the variability in the SOD rate of smaller sediment particles is greater since there is a higher amount of volatile solids (carbon) in the mud sediments than other sediment types. Even though there is a positive correlation between the SOD rate and the TVS, the role that the particle size of the sediments play in influencing Lake Erie's SOD rate can be seen. In addition, the TS, which are highly correlated with the TVS (r = -0.78, P = 0.0001), are also negatively correlated with the SOD rate (r = -0.56, P = 0.004) indicating that the easily suspended sediments containing high fractions of volatile solids contributed quite significantly to the SOD rate.

Correlations with Benthos and Sediment Grain Size

A positive correlation appears between the PHI value and the logarithmic number of total macroinvertebrates was found. An r^2 of 0.58 (P = 0.0003) indicates that the organisms preferred to occupy the smaller silt and clay sediments rather than the larger gravel or sand substrates. Although the correlation coefficients are not particularly strong, the oligochaetes, which comprise 86 percent of the benthic population, are found more often in sediments containing a greater proportion of clay sediments seen by a correlation coefficient of $r = 0.31$ and probability of $P = 0.06$ between the oligochaetes and the percent clay in the sediments. This relationship is also found, less strongly, by the oligochaetes' correlation with the PHI value ($r = 0.29$, $P = 0.10$).

The greater inhabitance of fine-grained sediments also appears to exist with the amphipods displaying a correlation coefficient of $r = 0.29$ ($P = 0.10$) when correlated with the PHI value. A correlation coefficient of $r = 0.36$ ($P = 0.03$) with the percent silt content of the sediments, suggests that the amphipods are found more often in the silt sediments, and less in the sand substrates ($r = -0.32$, $P = 0.06$). As a result both the amphipods and the oligochaetes inhabited the sediments with the smallest percentage of total solids. As mentioned previously, the smaller grain-sized sediments contain a larger amount of total volatile content ($r = 0.77$, $P = 0.0001$). In addition, the correlation between the number of benthos and the total volatile solids is $r = 0.49$ ($P = 0.004$), indicating that the availability of detritus (high TVS content) as a food supply does affect the location of the benthic populations. In other words, the benthos inhabit the clay and silt sediments due to the potential food supply.

The diptera, however, which were not numerically a significant part of the benthos ($r = 0.12$, $P = 0.8989$) had a slight preference for the more consolidated sediments which were also the sediments which contained a greater percentage of sand. No values on the benthic biomass were available.

Several investigators have noted the selectivity of benthic species for a particular substrate (Cummins and Lauff 1969; Wene 1940; Linduska 1942; and Pennack and Van Gerpen 1947). Due to the lack of time available for relating each species to their habitats, the only conclusions that will be made at this time will be those evident through Table 9 and the discussion in the above section. A thorough analysis of the relationship between sediment particle size, benthic macroinvertebrates, TVS, TS, and aerobic heterotrophic bacteria in the sediments to determine their combined effects on the SOD was processed using a multiple regression technique and will appear later in this paper.

Multiple Regression Analysis and Evaluation.

Explanation of Results.

The purpose of the multiple regression analysis is to formulate a practical and predictive mathematic model for the SOD rate in Lake Erie and further explain the relationship of the variables with the SOD rate. The correlation coefficients examine linear relationships between single variables, of which several could be correlated to each other to explain just one result. The multiple regression considers all the measurements and variables and indicates which of these variables actually affect the SOD rate. Three models were chosen to express the 1978 SOD rates under different conditions and only one was chosen for 1979. The first model for 1978 can be used under common environmental conditions in the lake. The second model includes the variable "stratification" which represents whether or not the water column above the sample site is stratified. The third model is used only under stratified conditions and explains what factors can account for the SOD rate during stratification throughout the lake at a particular time.

The variables chosen for the final equations used in the models give a great insight into how the SOD rate is affected by different factors. For 1978, the first equation has variables which are all positively correlated with the SOD rate (Table 22). The variables benthos, total volatile solids, total phosphorus and iron in the sediments, and the bottom temperature have all been quite thoroughly discussed throughout the text in correspondence with their effects on the SOD rate.

The second model (Table 22) once again contained variables which were all positively correlated with the SOD rate. The only changes in this model from the first model was the inclusion of the total sediment manganese for the total sediment phosphorus. They may both be indicators of the degree of resuspension of the sediments. Stratification was used instead of the percent total volatile solids, because the stratification accounted for the variation in the SOD rate more than the total volatile solids did, probably since the stratification takes into account the interaction of several variables instead of the effect of just one.

The variables involved in the final equation for the third model are quite interesting. The PHI value of the sediments was chosen, perhaps reflecting the importance of the benthos and the inorganic chemicals in the sediments, all of which are correlated with the grain size distribution. The percent total solids of the sediments is finally chosen, which reflects the resuspension of the sediment containing the inorganic chemicals. The total phosphorus in the hypolimnetic waters could be an indicator of the decomposition of seston that had fallen on the sediments and the subsequent liberation of phosphorus (Hutchinson 1957). The decomposition of seston would lead to an increased SOD rate, thus the relationship between hypolimnetic phosphorus and the SOD rate.

The remaining two variables in the equation are negatively correlated with the SOD rate. The distinction between the temporal measurements of 1979 and spatial distribution

TABLE 22

MULTIPLE REGRESSION TECHNIQUE EQUATIONS

1978

1) $0.45 \log B + 0.06\ V + 0.003\ P + 0.00003\ Fe + 1.28\ TVS - 4.98 = \text{SOD rate}$

where B = number of benthos
TVS = % total volatile solids (sediment)
P = total phosphorus (sediment)
Fe = total iron (sediment)
T = bottom temperature

$R^2 = 0.68$ $P = 0.004$

2) $1.75\ S + 0.002\ Mn + 0.004\ Fe + 3.37 \log T + 0.88 \log B - 13.25 = \text{SOD rate}$

where S = stratification (1 = yes; 0 = no)
Mn = total manganese (sediment)
Fe = total iron (sediment)
T = bottom temperature
B = number of benthos

$R^2 = 0.80$ $P = 0.0002$

3) $0.13\ Phi + 0.02\ TS + 0.01\ TP - 1.69 \log DO - 3.07L + 2.46 = \text{SOD rate}$

where Phi = sediment phi value
TS = % total solids (sediment)
TP = total phosphorus (hypolimnion)
DO = bottom DO
L = % incident light reading sediments

$R^2 = 0.87$ $P = 0.006$

1979

4) $0.50 \log DO - 0.27 \log chla - 0.04\ TSS + 0.38\ TVS - 0.0001\ H - 0.22 = \text{SOD rate}$

where DO = hypo DO
Chla = corrected chlorophyll a concentration
TSS = % total suspended solids (sediment)
TVS = % total volatile solids (sediment)
H = time of day

$R^2 = 0.70$ $P=0.0001$

of 1978 must be remembered. As previously mentioned, the 1978 measurements do not give any indication of the relationship of the DO to the SOD rate with time, and if measured throughout the stratified months at each station would show a decreasing SOD rate and DO concentration for each station. The reason the DO concentration is negatively correlated in 1978 is due to the lower DO concentrations being in areas of higher oxygen consumption by the sediments. This is only reasonable in spatial sampling since the DO must be lower in some areas than others during stratification due to oxygen losses of one kind or another. The inverse relationship between the SOD rate and DO suggest these oxygen losses are represented by the sediment oxygen uptake.

The percent light reaching the sediments is the last variable in this model. Its relationship with the SOD rate has been discussed in detail throughout the text but its contribution is too small to be considered as evidence that the algae in the hypolimnion can produce sufficient amounts of oxygen to significantly affect the SOD rate.

The model chosen for the 1979 data (Table 22) represents a predictve equation for the SOD rate in the middle of the central basin at any time during stratification. The variables appearing in the equation were the DO, corrected chlorophyll a, total suspended and volatile solids in the sediments and the time of day.

As discussed throughout the 1979 data, the positive relationship between the DO and the SOD rate is due to the slower diffusion of oxygen to the sediments at lower oxygen concentrations and, at very low DO concentrations, the oligochaetes and bacteria slow their oxygen consumption and eventually switch to fermentation requiring no oxygen. The total volatile solids is positively related to the SOD rate as expected through decomposition. The sediments with the lower suspended solids content can contain a greater amount of volatile solids by weight as compared with sediments containing higher suspended solids. This explains why the sediments with less suspended solids have a higher SOD rate. The SOD rate decreases with higher concentrations of corrected chlorophyll a since the algae (chlorophyll a) may be able to photosynthesize, producing enough oxygen to offset the SOD rate. This is supported by the SOD rate being slightly (although insignificantly) greater during the night than during the day.

Application of Models and Use of the SOD Rate as a Trophic Indicator. Most important is the possibility that these models may be used to predict Lake Erie's SOD rate under various conditions. Also, they may be applicable to other eutrophic bodies of water, but the use of these models has yet to be tested. It is my hope that in the near future these models will be fully tested, and revised where needed, for their practicality and applicability in predicting Lake Erie's, as well as other lentic waters', sediment oxygen demand rate.

The measurement of the SOD rate is an essential measurement for most limnological studies so one can better understand the system involved. It describes the major oxygen depletion process in many bodies of water and coupled with the WOD rate measurements will present the entire oxygen depletion process in almost all bodies of water.

The use of the SOD rate as a measure of the trophic state of a lake is very important. However, the SOD rate must be used along with other measurements, particularly the WOD rate, to assess the true condition of the lake. The use of the WOD rate alone will tell us no more than the use of the SOD rate alone, but applied together can yield quite crucial information. These in-situ oxygen demand measurements overestimate the overall hypolimnetic oxygen loss in Lake Erie's central basin during stratification due to oxygen sources from the eastern basin hypolimnion, central basin mesolimnion, and possibly by oxygen production from algal photosynthesis and entrainment from the western basin. In stratified lakes which display a relatively "closed system" these in-situ oxygen demand techniques will accurately estimate the hypolimnetic oxygen depletion rate.

A measurement called the areal hypolimnetic oxygen deficit (g O_2 $m^{-2}d^{-1}$) which, by measuring the hypolimnetic oxygen depletion on an areal basis, allows for direct comparison of the amount of oxygen depletion in different lakes. However, this measurement does not take into account the volume or thickness of the hypolimnion which, as seen in this investigation, can vary resulting in different degrees of actual oxygen depletion. In other words, if the areal hypolimnetic oxygen deficit rates are equal in two lakes, one with a deep hypolimnion and the other with a shallow hypolimnion, the oxygen will be depleted sooner in the lake with a shallow hypolimnion.

I am not implying that the areal hypolimnetic deficit rate is not a valuable measurement because it happens to be a quite useful tool in understanding and classifying a trophic system of a lake. I believe that a knowledge of the volumetric oxygen depletion rate is also essential, particularly in Lake Erie, and gives an added dimension to the areal rates by being able to predict when a severe oxygen concentration may be reached. All that is needed to know to calculate the volumetric oxygen depletion rate from the areal rate is the hypolimnetic thickness which is divided into the areal rate to give a volumetric depletion rate expressed in mg $O_2l^{-1}d^{-1}$. By conducting in-situ oxygen depletion measurements, the WOD rate is already in volumetric units and the areal SOD rate can then be converted to the volumetric SOD rate.

As previously discussed, the SOD rate must be measured along with the WOD rate to give an understanding of the oxygen depletion processes and to predict when the DO may be severely depleted. The volumetric measurements can be considered an indirect measurement of the trophic state, dependent upon the hypolimnetic thickness. The actual employment of the areal SOD rate to measure eutrophication is one of giving a minimum value of the possible oxygen demand. However, if the areal SOD rate exceeds the limits set by Hutchinson or Mortimer (1.3 g O_2 $m^{-2}d^{-1}$ or 0.55 g O_2 $m^{-2}d^{-1}$ respectively; Hutchinson, 1957) then this would clearly indicate a eutrophic condition; the severity depending on the contribution of the water column oxygen demand.

RECOMMENDATIONS

Methodology

The major problems with the *in-situ* SOD rate measurements conducted in this, and similar studies, are (a) the resuspension of the sediments during placement of the chamber, (b) assurance that the chamber completely sealed in the sediments, (c) the minimal length of individual experiments due to the depletion of oxygen in the chamber within a few hours and (d) the great difficulty in measuring the SOD rate with initial DO levels below 3-4 mg O_2/l and (e) simulating the natural environment within the chamber (current velocities and natural sediment resuspension).

The resuspension of the sediments can be dealt with by either increasing the size of the flanges for easier and softer contact with the sediment surface and/or allowing sufficient time before beginning the SOD rate measurements for the oxidation of the exposed inorganic chemicals.

To solve the problem of complete oxygen depletion within the chamber, the use of an electrolytic respirometer which continuously replaces the oxygen consumed is recommended. Although this method is costly, it should prove useful in determining SOD rates and their fluctuations for periods of up to 12 hours at a time and will yield more accurate rates. In addition, the electrolytic respirometer will allow actual SOD rate measurements to be made below 3-4 mg O_2/l. There are two methods which should be employed. First, the ambient SOD rate should be measured using the regular procedure, and then it should be measured by entraining well-oxygenated epilimnion or hypolimnion water to be able to compare rates with other values under well-oxygenated (5 mg O_2/l) conditions. By entraining well-oxygenated waters into the chamber the ensuing measurements are those of the oxygen demand rate of the sediments if sufficient oxygen is present. The SOD rate measured with the regular procedure indicates the rate at which oxygen is actually being consumed at the sediment-water interface which may not actually be its "demand," but the oxygen "uptake," since there might not be enough DO present to satisfy the oxygen demand.

Proper circulation within the chamber must closely represent that in the natural environment if reliable SOD rates are to be obtained. A uniform circulation is also needed to ensure complete mixing of the water within the chamber to prevent microstratification.

Further Studies

The relationship of the oxygen concentration with the SOD rate needs to be examined, and perhaps the use of the electrolytic respirometer will be the essential improvement in the analysis. Both *in-situ* and laboratory studies should be conducted under varied sediment parameters including organic content and benthic macroinvertebrate populations as well as different oxygen concentrations of the overlying water to determine more accurately how these variables affect one another.

Additional research needs to be conducted on the effects of algal photosynthesis upon the SOD rate to determine the limiting factors involved. The parameters to be considered in such an investigation are the intensity and quality of the incident light, the percent of the incident light reaching the sediments as well as the algal populations measured by the corrected chlorophyll *a* concentrations and plate counts. Also, controlled experiments using both translucent and opaque chambers as well as plexiglass tubes, need to be made to evaluate any differences that may exist for the SOD rates in the translucent and opaque containers under varying light intensity, algal populations and sediment parameters to further define the SOD rate-algal photosynthesis relationship.

The mathematical equations derived in this study to express the SOD rate in the field need to be tested thoroughly and improved for wider applicability. Studies also need to be done to further define the relationships found and hopefully suggestions made in this paper will provide some insight on how to accomplish this.

CONCLUSIONS

From the Spatial Sampling in 1978 it is concluded that:

1) The mean sediment oxygen demand rate (g O_2 $m^{-2}d^{-1}$) for each basin was 2.45 for the western basin, 1.08 in the central basin and 1.41 for the eastern basin.

2) The SOD rate of the western basin is greater than that of the central and eastern basins owing to higher temperatures; correcting the SOD rates for temperature (10°C), there is no significant difference between the SOD rates for each basin.

3) The SOD rate increases with the number of benthic macroinvertebrates in the central and eastern basins, most likely due to respiration or bioturbation.

4) Sediments having a high 0 value (small grain size diameter) yield higher SOD rates due to (a) the resuspension of the sediments exposing reduced inorganic chemicals for oxidation; (b) the silts and clays containing a higher percentage of organic matter, and (c) the benthic macroinvertebrates found in the smaller grain size sediments.

5) Sand and glacial till sediments (large grain size diameter) have approximately fifty percent lower SOD rates than smaller grain size sediments because the sands and glacial tills have (a) a smaller amount of organic matter and (b) lesser amounts of benthic macroinvertebrates.

6) Higher concentrations of total phosphorus, total manganese and total iron in the sediments reflect increased SOD rates when factors such as hypolimnetic water currents and the degree of sediment resuspension during chamber placement become significant.

Conclusions from the Temporal Measurements in 1979:

7) Sediment oxygen demand and water column oxygen demand are both significant contributors to Lake Erie's hypolimnetic oxygen depletion.

8) The mean SOD rate for the stratified period was 0.95 g O_2 $m^{-2}d^{-1}$ and the mean WOD rate for the same period was 0.14 g O_2 $m^{-3}d^{-1}$.

9) The total oxygen demand (TOD) rate in the hypolimnion was found not to be significantly ($P = 0.05$) different throughout stratification and averaged 0.36 g O_2 $m^{-3}d^{-1}$.

10) The SOD rate decreases with the hypolimnetic oxygen concentration in August (cruise three) probably due to two factors: (a) slower diffusion of oxygen to the sediments at lower DO concentrations and (b) lower oxygen consumption by benthic macroinvertebrates below 2-3 mg O_2l^{-1}.

11) The hypolimnetic WOD rate increases throughout stratification due to algal respiration and decomposition.

12) The measured in-situ oxygen demand rates differ from the calculated cruise interval oxygen demand rates because the in-situ rates measure the actual process of oxygen depletion while the cruise interval technique measures the overall effects of the oxygen depletion.

13) The cruise interval measurements are consistently lower (approximately two times lower) than the in-situ measurements because of a large oxygen input from sources including (a) transfer of cold, oxygen-enriched hypolimnetic water from the eastern basin and (b) entrainment of well-oxygenated water from the central basin mesolimnion.

14) Although under proper conditions photosynthetic algae may produce enough oxygen to offset the SOD rate, these conditions did not occur often enough or in great enough quantities during the times sampled to be considered as a significant oxygen source to the central basin hypolimnion during this study.

Conclusions from the Evaluation of Methodology and Application of the SOD rate measurements:

15) To considerably improve the methodology concerning SOD rate measurements, it is recommended that an electrolytic respirometer should be used instead of the electronic oxygen probe, which by continuously replacing the oxygen consumed would (a) allow the actual oxygen uptake rate to be measured in areas with a low DO concentration and (b) eliminate the problems associated with rapid oxygen depletion within the SOD chamber allowing for a longer experiment time and more accurate SOD rates.

16) The use of the SOD rate as a trophic indicator in lakes is quite essential, but it must be measured along with the WOD rate to give an understanding of the oxygen depletion processes in order to predict when the DO may be severely depleted. The employment of the SOD rate alone to determine eutrophication only provides a minimum value of the possible oxygen demand, but if the rate is high enough it can indicate the severity of oxygen depletion. The true degree of oxygen depletion depends upon the contribution of the water column oxygen demand.

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APPENDIX 1: SELECTED METHODS

A. Sediment Aerobic Heterotrophic Bacteria Methods (1978)

Object:

1. Total aerobic heterotroph enumeration by plate count.
2. Total bacterial enumeration by direct observation.

Procedure: (Partly from Babiuk, L. A. & E.A. Paul. 1970. The use of FITC in determination of bacterial biomass of grassland soil. Canadian Journal of Micro 16, 57-62).

1. Weigh out 15g sediment from 'top' of ponar.
2. Blend with 150 mls sterile 0.1% peptone for 3 min.
3. Dilute to 10^{-6}.

For plate count:

1. Put 0.1 ml of proper dilution on plate, spread with L-rod. Let dry. Put in zip-lock bags and incubate for 14 days at 23°C. Check at 7 days.

2. Dilutions to be done:
   2 plates of 10^{-3}, 10^{-7}
   4 plates of 10^{-4}, 10^{-5}, 10^{-6}

3. On days 7 & 14 count the number of colonies present. Check the "fuzzy" colonies under microscope to determine if they are actinomycetes or molds/fungi.

For direct microscopy:

1. Put 0.01 ml of 10^{-2} dilution on 1 cm^2 area of the slide. Do two squares per station. Air dry, heat fix slightly.

2. Stain with FITC for 3 min. Wash with .5 ml Na_2CO_3 10 min., wash with 5% sodium pyrophosphate for 2 min., and rinse with DDH_2O. Drop glycerol (buffered) on slide and store at 0°C in dark.

3. Observe on UV microscope 10-14 days later (or as soon as possible).

Control on sterility

1. Prepare balance and blender as usual (alcohol, flame).
2. Blend peptone H_2O after rinsing balance pan with it.
3. Dilute 2 plates each of 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}.
4. Let one plate be exposed to air 8 min.
5. Incubate one uninoculated plate.
6. Incubate all plates 14 days 23°C.

Recovery Study (how many bacteria are we really getting out?)

1. Sterilize mud.
2. Add Bacillus subtilus (a normal soil organism) to 2 of 3 mud samples, let sit 3 hrs.
3. Blend, dilute and plate as above.
4. Titer bacteria culture.
5. Incubate at 23°C.
6. Compare counts.

APPENDIX 1 (CONT.)

B. Sediment Aerobic Heterotrophic Bacteria Methods - 1979

Sediment and water samples were obtained by diver using a 11.5 cm x 45 cm hand core. The cores were settled for approximately 2 hours. Water subsamples were taken from one centimeter above the interface, diluted in phosphate buffer (standard methods) and plates on plate count agar using the membrane filtration (mf) method. Plates were incubated at 20°C for three days. Colonies were counted with the aid of 10x magnification and reported as cells/100 ml.

Sediment samples were taken from the interface using a pipet. A ten ml alliquot of sediment was dispersed in 100 ml phosphate buffer (standard methods). This suspendsion was diluted and pated on Trypticase Soy Agar using the spread plate technique. Plates were incubated for 4 days at 20°C and counted with the aid of a 2x magnification. Counts were recorded as cell/g wet weight sediment.

Objectives: To ascertain the relationship between oxygen demand of sediments in central Lake Erie and the number of Total Heterotroph bacteria.

Procedures:

1. A hand core was taken by divers and allowed to settle for approximately 1-2 hours.
2. Subsampling:
    a. Two - 1 ml alliquots of water were removed from 1 cm above the interface.
    b. Three - 10 ml alliquots of sediment were taken from the interface and placed in 100 mls sterile phosphate buffer, shaken vigorously to dispense.
3. Diluting:
    a. Water Sample
        1. Both samples diluted in sterile phosphate buffer, 10^{-2}, 10^{-3}, 10^{-4}.
    b. Sediment Sample
        1. Samples diluted in sterile phosphate buffer, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}.
4. Plating:
    a. Water Sample
        1. Use of mf technique
            a. Sterile milipore filter holder for each sample.
            b. Milipore HAWG .47 um filters used.
            c. Sterile phosphate (standard methods) buffer in squeeze bottle was used to rinse filter holders.
            d. Dilutions filtered in increasing concentrations (10^{-4}, 10^{-2}).

        e. Filters placed on plate count agar and incubated at 20°C for 3 days.

        f. Colonies counted u/10x magnification

5. Sediment Sample:

    a. Use spread plate technique

        1. 0.1 ml of each dilution put sterilely on TSA (Tryptone Glucose yeast extract) agar plates.

        2. Spread with sterile glass rod in increasing concentration.

        3. Incubate for 4 days at 20°C.

        4. Count colonies u/2x magnification.

    b. A fourth sediment was placed in a sealed screw-top test tube to be weighed at the laboratory.

6. Counts reported:

    a. Water Sample - cells/100 ml H_2O.

    b. Sediment Sample - cells/100 ml sediment and cells/g wet weight sediment.

APPENDIX 1 (CONT.)

C. Water Column Oxygen Demand (Microwinkler Technique)

1. Fill microwinkler bottle according to winkler procedure (CLEAR, 1978). Fill 6 light and 6 dark bottles for each depth.
2. Record bottle number on data sheet and its corresponding depth prior to inserting 3 light and 3 dark bottles into the 6-armed bottle holder (tree).
3. Place foil over light bottles to avoid light shocking algae. Foil will be removed by divers once the tree is submerged.
4. Suspend to desired depth.
5. Prep the 3 light and 3 dark bottles remaining from each depth. These values are to be recorded as initial readings. To each 300 ml BOD gottle add 2 ml of $MnSO_4$ and 2 ml of azide, making sure each is injected below the surface. A brown precipitate will form. Let it settle. Shake well (10 times). Let it settle a second time before adding 2 ml of concentrated H_2SO_4. An amber color will form.
6. Using a 50 ml volumetric pipet, transfer a 50 ml aliquot into a 125 ml erlenmeyer flask with the bottom painted white. Do not transfer sample until it has reached room temperature. Do not rinse 50 ml pipet, just shake it out.
7. Titrate "initial" microwinkler samples using a 5 ml microburet (.01 ml div.), .025 N HCl as the titrant, a glass rod and a magnetic stirrer.
8. Prep for 2nd set of microwinklers. Only dark bottles will be utilized for night experiment.
9. Pull up daylight microwinklers and fix them. Let them sit until reaching room temperature before proceeding.
10. Titrate initial microwinklers for the 2nd set while you are waiting.

APPENDIX 1 (CONT.)

D. Benthos

Methods

Macrobenthic organisms were collected by the use of a 23 x 23 cm Ponar dredge. Deep water samples were raised by the use of a power winch aboard the R/V Hydra. Shallow stations sampled from a smaller power boat were raised by hand and stored in plastic bags. The shallow water samples were then taken aboard the R/V Hydra, where they were sieved along with the deep water samples.

The samples were seived through a number 30 USGS standard sieve (0.91 mm openings) using the boat's hose and lake water. The material retained by the sieve was transferred to plastic jars and preserved with 10 percent formalin and then transported to the laboratory for identification.

Laboratory Methods

At the laboratory a solution of Rose Bengal and ethyl alcohol was added to each sample to stain the animal organic matter pink, which contrasts with the substrate. The staining process was allowed to continue for at least 24 hours before the organisms were picked from the sample. To insure that all species and organisms are accounted for and that skewed results do not occur in favor of dominant species, benthos were removed from the entire sample. Each sample was rinsed in a sieve and then poured into a white enamel pan. The substrate was flushed with water several times and the water poured into a fine mesh sieve (40 mesh). This process was repeated several times until visual observation indicated the absence of organisms in the substrate. A careful check of the substrate randomly insured a recovery of 95 to 100 percent of benthos in each sample. This method proved efficient for the smaller benthos, which constitute a larger total percentage of organisms. The sieve was then rinsed into a clean enamel pan and the benthos placed in numbered vials of 70 percent ethanol for later identification.

The contents of each vial were placed in a plastic petri dish for gross identification under a 15 to 30 power, dissecting microscope. This stage of identification was used to separate immature and mature oligochaetes and for identification of larger benthos (i.e., amphipods, oligochaetes, leeches, etc.). Representative specimens of chironomid genera were wet mounted for examination of the head capsule. This is a recommended method where large numbers of midges are to be identified. The clearing of head capsules is not usually necessary for identification to the generic level because of morphological features specific to each of the existing genera. At this point any unidentified species were retained for further examination and the rest were stored.

Adult oligochaetes were placed in an ascending alcohol series to prepare them for permanent slides. The procedure to fix the specimens is to add 70 percent ethanol for 24 hours, 95 percent ethanol for 2 hours, 100 percent ethanol for 2 hours and xylene for 12 hours. Oligochaetes were finally mounted in Permount. Each slide was labelled with station number and allowed to dry for 48 hours. Identification was made using a compound microscope with special attention given to the setae size and shape along with size and shape of sex organs.