U.S. Department of the Interior
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Sediment Oxygen Demand in Upper Klamath and Agency Lakes, Oregon, 1999

Water-Resources Investigations Report 01–4080

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Upper photographs:

Sediment oxygen demand chamber on boat and being deployed.

Lower photograph:

Divers examine sediment core samples.

U.S. Department of the Interior
U.S. Geological Survey

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By TAMARA M. WOOD

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Portland, Oregon: 2001

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Suggested citation:

Wood, T.M., 2001, Sediment oxygen demand in Upper Klamath and Agency Lakes, Oregon, 1999: U.S. Geological Survey Water-Resources Investigations Report 01–4080, 13 p.

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
centimeter (cm)	0.394	inch (in)
meter (m)	3.28	foot (ft)
square kilometer (km^2)	.386	square mile (mi^2)
liter (L)	.0353	cubic feet (ft^3)
milligrams per liter (mg/L)	1	parts per million (ppm)

Sediment Oxygen Demand in Upper Klamath and Agency Lakes, Oregon, 1999

By Tamara M. Wood

SIGNIFICANT FINDINGS

- The distribution of SOD_{20} values (measured sediment oxygen demand values corrected to 20°C [degrees Celsius]) had a median value of 1.6 g/m²/day (grams per square meter per day) in the spring and 1.7 g/m²/day in the late summer. These values were well within the range of values in the literature for sites with similar sediment characteristics: primarily silty with at least a moderate amount of organic content.
- Over most of the lake there appears to be relatively little variation in SOD—the interquartile range in values was 0.4 g/m²/day in the spring and 0.7 g/m²/day in the late summer. A significant exception was apparent in Ball Bay, where SOD in the late summer was greater than 10.2 g/m²/day. In the absence of primary production, an SOD of this magnitude could deplete the water column of oxygen in a few days. This measurement provided evidence that localized areas of very high SOD occur episodically in the bays, perhaps associated with large algal mats being trapped by the lake circulation patterns.
- A statistical test for a spring to late summer difference in the median values of SOD confirmed that SOD in the late summer (median value 1.7 g/m²/day) was significantly higher than in the spring (median value 1.2 g/m²/day). The difference was primarily due to seasonal changes in temperature; when SOD values were corrected to 20°C, there was no seasonal difference in the median values.
- There was no correlation between SOD_{20} and the sediment characteristics measured in this study: percent fines, organic carbon, and residue lost on ignition.

INTRODUCTION

Low dissolved oxygen concentrations (less than 4 milligrams per liter) have been documented in Upper Klamath and Agency Lakes, where they are detrimental to the survival of endangered sucker species in the lakes. The Bureau of Reclamation and the Klamath Tribes have been collecting water-quality data in Upper Klamath and Agency Lakes since 1988. These data indicate that dissolved oxygen concentrations low enough to be of concern are most likely to occur in late summer, after large algal blooms have started to decline. The lowest dissolved oxygen concentrations are most likely to occur near the bottom of the water column; however, low concentrations have been measured at and near the surface as well (Wood et al., 1996; also Wood, unpub. data).

Upper Klamath Lake (fig. 1) is a large (360 km² [square kilometer]), shallow (mean depth about 2.4 m [meter]) lake in south-central Oregon that the historical record indicates has been eutrophic since at least the beginning of the 20th century. In recent decades, however, the lake has had annual occurrences of near-monocultural blooms of the blue-green alga *Aphani-*

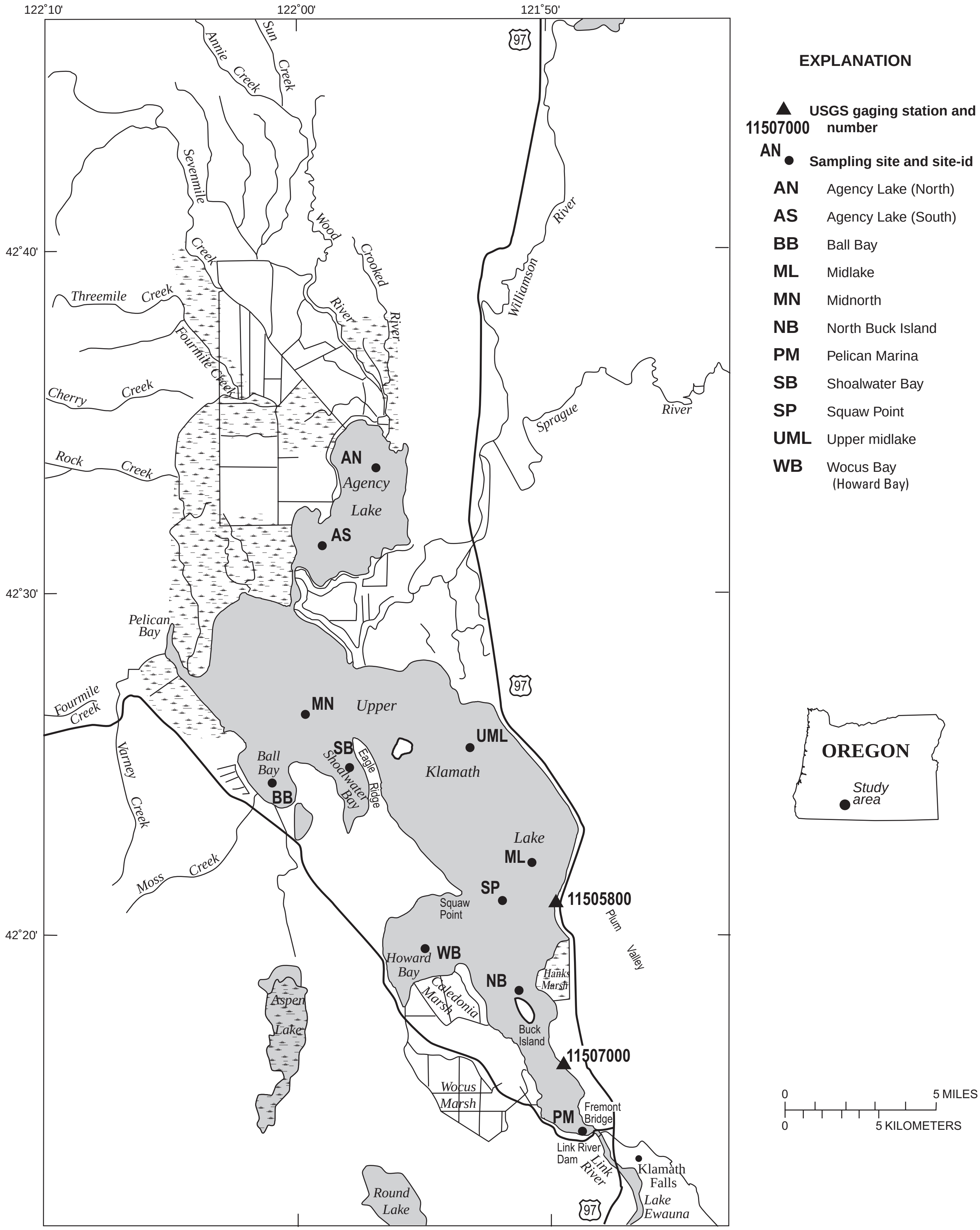

Figure 1. Upper Klamath and Agency Lakes, Oregon .

zomenon flos-aquae. In 1988, the Lost River sucker and the shortnose sucker, which live primarily in the lake and spawn in its tributaries, were listed as endangered by the U.S. Fish and Wildlife Service under the Endangered Species Act. The poor water quality associated with the extremely long and productive blooms is contributing to the decline of those fish species (Perkins et al., 2000).

The water-quality monitoring data collected to date have not been adequate to quantify the various mechanisms that influence dissolved oxygen concentrations—most notably photosynthetic production, respiration, sediment oxygen demand (SOD), carbonaceous biological oxygen demand (CBOD) in the water column, reaeration, and resuspension of oxygen demanding bed sediment. The scope of this work is the quantification of one piece of the oxygen budget—SOD. SOD operates on a longer time scale than the highly dynamic processes of algal photosynthesis and respiration. It is to be expected that daily fluctuations in dissolved oxygen would be dominated by those algal processes. SOD is nonetheless important because it provides a “background” oxygen demand onto which the other more dynamic oxygen demands are superimposed, thereby enhancing, for example, the oxygen-demanding effects of algal respiration and CBOD, and limiting the effectiveness of oxygen-producing photosynthesis. The SOD rate is also an important rate required for efforts to model dissolved oxygen, nutrients, and algae in the lake.

While the SOD is stable when compared to the highly dynamic processes associated with algal metabolism, it might be expected to vary on seasonal time scales—because SOD is determined by sediment characteristics, the settling of new sediments on an annual cycle could change the SOD associated with those sediments. Newer sediments, having undergone less decay than older sediments, have the potential to create a higher oxygen demand as they are richer in unmetabolized organic nutrients. In a eutrophic lake like Upper Klamath, the sediments are largely composed of algal detritus; fresh sediments are produced on an annual cycle when the bloom crashes in the late summer and fall.

Of particular interest in Upper Klamath Lake is the role that lake management might play in producing low dissolved oxygen concentrations. Lowering lake levels through the summer can potentially enhance the net effect of sediment oxygen demand (SOD) on water column dissolved oxygen by increasing the bed sediment area to lake volume ratio. Lake managers at the Bureau of Reclamation (BOR) can establish minimum lake levels in the hope of reducing sediment resuspension and/or providing more water volume to dilute the effects of the SOD. Given a measured value of SOD and realistic assumptions about reaeration rates and the frequency of lake mixing, the BOR will be better able to assess the likelihood that controlling lake levels will reduce the frequency of occurrence of very low dissolved oxygen concentrations.

The objectives of this study were:

- To determine the magnitude and variability of SOD in Upper Klamath and Agency lakes.
- To determine the change in SOD from before the development of summertime algal blooms to late summer, after or during the decline of the blooms.
- To attempt some correlation between measured SOD and other quantifiable sediment characteristics, in particular: coarse/fine distribution, organic carbon content, and the residue lost on ignition.

METHODS AND PROCEDURES

The design of the chambers used in this study (fig. 2) and the procedures for their deployment and the collection of the data have been described in detail elsewhere (Rounds and Doyle, 1997; Caldwell and Doyle, 1995; original design by Murphy and Hicks, 1986). In brief, the chambers are opaque plastic cylinders (56 cm diameter), open on the bottom, with a metal collar around the bottom rim to allow them to be

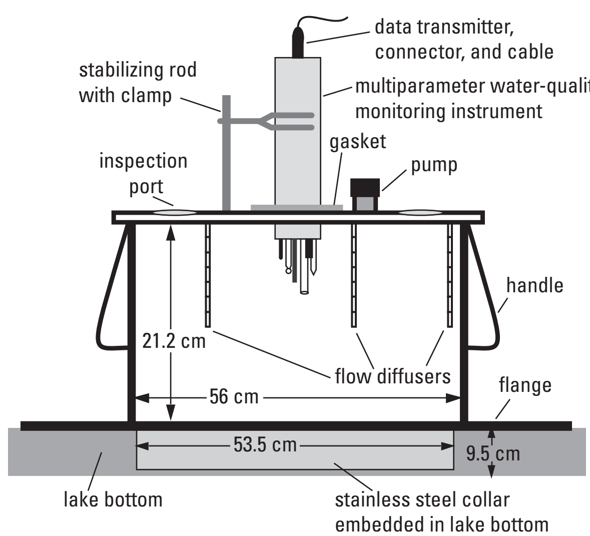

Figure 2. Schematic diagram of the chambers used to measure sediment oxygen demand in Upper Klamath Lake.

seated into the bottom sediments. Once the chamber is sealed, water is continually recirculated through the chamber via a pump-driven system consisting of an intake and output through three flow diffusers. A datasonde with a calibrated dissolved oxygen probe is mounted in the top through a gasket seal. A cable connection to the surface allows real-time data transmission. The volume of water that the chamber isolates over the bottom sediment is 52.5 liters. For use in Upper Klamath Lake, which has, in some areas, particularly "fluffy" (loosely consolidated) bottom sediments, an additional modification was made. A hole just the size of the stainless steel collar, not big enough for the rest of the chamber to fit through, was cut into a thick piece of plastic approximately 1 m square to create a flange. Each chamber was inserted into this hole before both the chamber and the flange were lowered into place by scuba divers. The additional surface area provided by the flange prevented the chambers from sinking into the sediments, and as a result the chambers were always ideally seated into the sediments.

After the chambers were lowered and seated, any disturbed sediments were allowed to settle for at least 10 minutes. At that point the chambers were purged for at least 10 minutes in order to fill the chamber with water from the surrounding near-bottom environment. After purging, the inspection ports were closed and valves were redirected in order to recirculate water inside the chamber. After closing the inspection ports, the dissolved oxygen concentration in the chamber was recorded at approximately 10-minute intervals for a 2-3 hour period.

Each chamber was equipped with a rheostat that allowed the pump circulating the water inside the chamber to be set to maximum capacity, 60% of maximum capacity, or 40% of maximum capacity. The optimum speed for operating the pump was determined in the spring through simple experimentation with a turbidity probe on one of the datasondes inside the chambers. Operating the pump at its maximum capacity resulted in an abrupt increase in turbidity that was associated with a resuspension of the sediments inside the chamber. Resuspension is not desirable as it increases the sediment oxygen demand of the water inside the chambers, and it obscures the sediment demand that the chambers are designed to measure. The divers also confirmed that resuspension of sediments did not occur outside of the chambers during the calm conditions that prevailed while the SOD data were collected. Resuspension did not occur when the pump was operated at 60% of capacity, so that was designated the optimum pump speed for these experiments. The lack of resuspension was confirmed by visual inspection of water samples obtained through the inspection ports by divers.

Sampling Design

Data were collected at 11 sites around Upper Klamath and Agency Lakes. All of these sites are established water-quality sampling sites where water-quality profile data or continuous water-quality measurements have historically been collected (fig. 1). The sites are at depths and locations that should represent conditions over most of both lakes. The sites were visited once in the spring, before the *A. flos-aquae* bloom had become fully developed, and once in the late summer when the *A. flos-aquae* bloom was in decline. Spring sampling took place between May 18 and May 27, 1999; late summer sampling took place between August 24 and September 1, 1999.

The SOD measurements were taken in triplicate by deploying three identical chambers at each site in order to provide an estimate of the mean SOD and a measure of intrasite variability. A single "blank" chamber was also deployed at each site to measure the small oxygen demand associated with the water overlying the sediments. The blank chamber is designed essentially the same as the SOD chambers, except that the stainless steel collar is replaced with a sealed plastic bottom. The procedure for deploying the blank chamber and collecting data from it is the same as for the open-bottomed chambers. The water column oxygen demand measured in the blank chamber was subtracted from the sediment oxygen demand measured in the open-bottomed chambers.

Samples of the surficial sediment next to each chamber also were collected by the divers. Small core samplers were constructed from a 15-cm long, 3.8 cm diameter section of cylindrical polycarbonate. This core sampler was pressed into the sediments by the divers until the top was flush with the top of the sediments, then removed carefully and capped at both ends with nylon caps. After the corer was brought to the surface, the sediment was removed, homogenized, and split so that a portion could be sent to the Cascades Volcano Observatory laboratory in Vancouver, Washington for analysis of the sand fraction and the residue lost on ignition (RLOI, Fishman and Friedman, 1989).

Another portion was sent to the USGS National Water Quality Laboratory in Denver, Colorado for analysis of organic carbon (OC), obtained by differencing total carbon obtained from combustion and inorganic carbon by coulometric titration (Arbogast, 1996).

Analysis of Sediment Oxygen Demand Chamber Data

The change in oxygen concentration with time in the chambers is linear after an initial period, usually less than 15 minutes, in which the change in oxygen concentration can be nonlinear and more rapid. This nonlinearity is usually attributed to the suspension of some sediment during the deployment and purging of the chambers; this sediment then settles back to the bottom within the first several minutes after the ports are closed. For this reason, any data from the first 15 minutes after closure of the SOD chamber ports were removed from the time series before analysis. Then a standard linear regression was run on all the remaining data to determine the slope of the line describing the rate of change of dissolved oxygen with time. That slope was used to determine the SOD with the equation:

$$SOD_T = 1.44\frac{V}{A}b, \qquad (1)$$

where SOD_T is the sediment oxygen demand in g/m^2/day at temperature T, b is the slope of the regression in mg/L per minute, V is the volume of the chamber in liters, A is the area of bottom sediment covered by the chamber in m^2, and 1.44 is a factor for units conversion. SOD at temperature T was adjusted to an SOD rate at 20ºC using a standard van't Hoff equation:

$$SOD_{20} = \frac{SOD_T}{1.065^{T-20}}. \qquad (2)$$

The procedure used to analyze the data from the blank chambers was identical.

Statistical Methods

A mean value was calculated from triplicate measurements of the sediment characteristics SOD, OC, percent fines, and RLOI. Error bounds are reported as plus and minus one standard deviation around the mean.

Correlations between variables were calculated using the ranks of the variables (a Spearman correlation) rather than their values, in order to allow for nonnormality in the datasets. Standard statistical tests were used to check for seasonal differences in several of the variables: analysis of variance (ANOVA), the Mann-Whitney (Wilcoxon) test, and Tukey's multiple comparison test (Helsel and Hirsch, 1992; SAS Institute, Inc., 1989). Sites where both spring and fall values were obtained were included in these tests (nine sites—Ball Bay, Shoalwater Bay, Midnorth, Upper Midlake, Midlake, Squaw Point, North Buck Island, Agency North, and Agency South). Seasonal tests were run on the averages of triplicate measurements. Rank transformations were used to increase the normality of the data distributions. Seasonal differences and correlations were considered significant when the probability of a Type I error (p) was <0.01.

WATER-QUALITY CONTEXT

The chlorophyll-*a* data collected as part of the routine monitoring of the lake by the Klamath Tribes confirmed that the collection of SOD data in the spring of 1999 preceded the onset of the bloom (fig. 3). The median chlorophyll-*a* concentration on May 12 and May 25 from the nine sites sampled regularly by the Tribes was 6 µg/L and 4 µg/L, respectively. Using a threshold value of 20 µg/L, the bloom was not detected until June 10, whereas spring SOD measurements commenced on May 18.

The collection of SOD data in the late summer overlapped with the first significant population decline of the algae in 1999, probably precipitated by a change in the weather. On August 31, the minimum daily air temperature fell below 30ºF for the first time since early July (the minimum air temperature was 43ºF on August 30, and 29ºF on August 31, as measured at the Klamath Falls Agricultural Station), and minimum daily temperatures remained in the 30's for the next week. On the 17th of August when the Klamath Tribes collected their routine monitoring samples, the median chlorophyll-*a* concentration around the lake was 84 µg/L, but by the next sampling date on September 1, the median chlorophyll-*a* concentration was down to 10 µg/L, indicating a crash in the algal population. On the subsequent sampling date, September 15, median chlorophyll-*a* was back up to 34 µg/L, indicating a

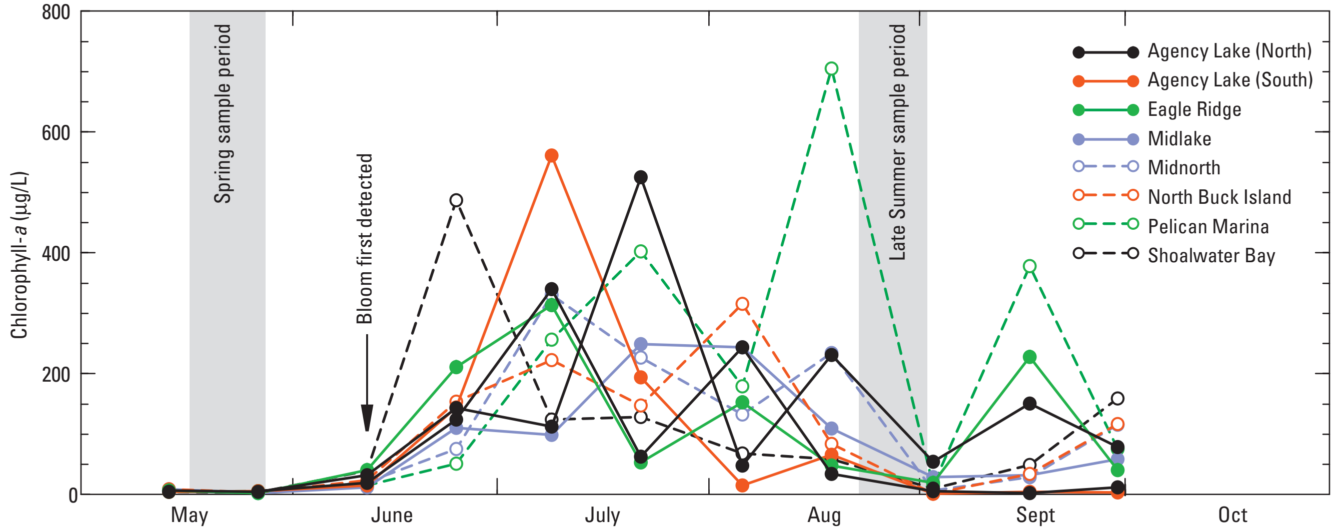

Figure 3. Chlorophyll-*a* concentration at selected sites, Upper Klamath and Agency Lakes, Oregon, May–October 1999.

recovery of the algal population; the collection of the SOD data during August 24 to September 1, however, likely occurred during a period when a rapid decline in the algal population was actively occurring. Profile data at both an open lake site (Midnorth) and a bay site (Shoalwater Bay) show that previously present vertical stratification collapsed sometime before the sampling on September 1 (fig. 4 and fig. 5). This was also the first date since June that photosynthetically elevated values of pH and dissolved oxygen were not measured at either of these sites. In general, the water-quality data indicate that photosynthetic activity was at a greatly reduced level during the period of time that the SOD data were collected in the late summer.

RESULTS AND DISCUSSION

The quality of the data from most of the sites was good, although there was variability among the three chambers deployed at a given site. Representative examples of a spring dataset and a fall dataset are shown in figures 6 and 7, respectively. The standard deviation of the SOD derived from both of these datasets was 0.3 g/m^2/day. At each of these sites the data from one or two chambers was very smooth, while the data from the third chamber was substantially more variable. The data in figure 7, however, exhibits the most variability found at any site on either date. A reasonable estimate of the SOD was obtained at all sites in the spring and summer, with three exceptions: (1) Pelican Marina data in the spring was not intercomparable with the other sites because the pump recirculating water through the chambers was not operating at the optimum speed, (2) no estimate was obtained at Howard Bay (also known locally as Wocus Bay) in August because the concentration of dissolved oxygen in the water at the start of the test was nearly zero, and (3) only a lower limit on the SOD could be obtained at Ball Bay in August because an exceptionally high oxygen demand resulted in the dissolved oxygen concentrations declining rapidly, at which point the low dissolved oxygen concentrations constrained the SOD and a good linear regression could not be obtained (fig. 8). The calculated SOD values and laboratory data from sediment samples are provided in table 1 (p. 9).

Over silty bottom sediments like those in Upper Klamath Lake, a similar range in SOD values has been measured in otherwise distinct environmental settings. A small sampling of the measurements of SOD by *in-situ* methods found in the literature is provided in table 2 to illustrate that the range in SOD_{20} measured in Upper Klamath Lake is similar to the range in values found by other investigators in varied river and lake settings. The feature common to all of these settings is a silty bottom with at least a moderate amount of organic content.

Spatial Patterns in Sediment Oxygen Demand

In general, the variability in the measured SOD around the lake was not large, the 25th, 50th, and

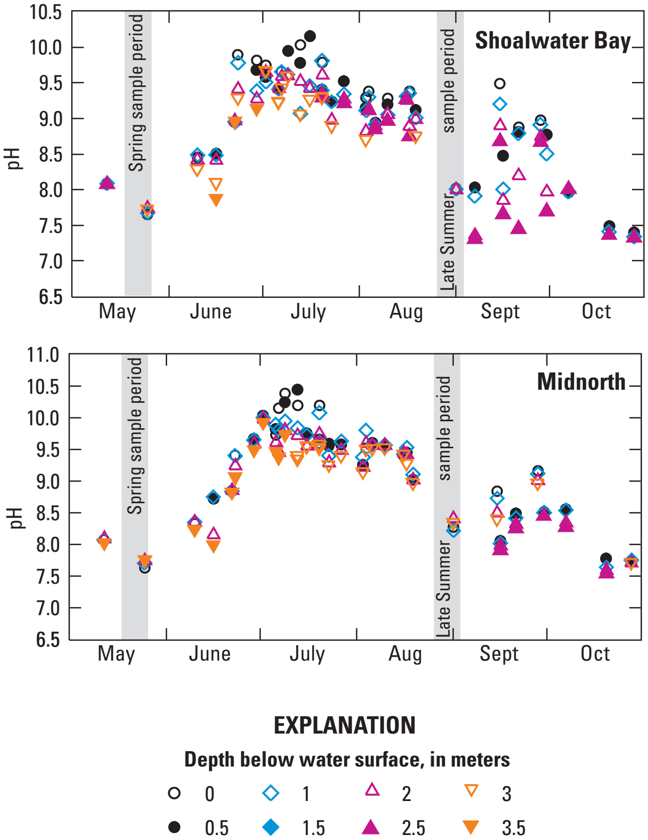

Figure 4. Depth-profile pH data at sampling sites Shoalwater Bay and Midnorth, Upper Klamath Lake, Oregon, May–October, 1999.

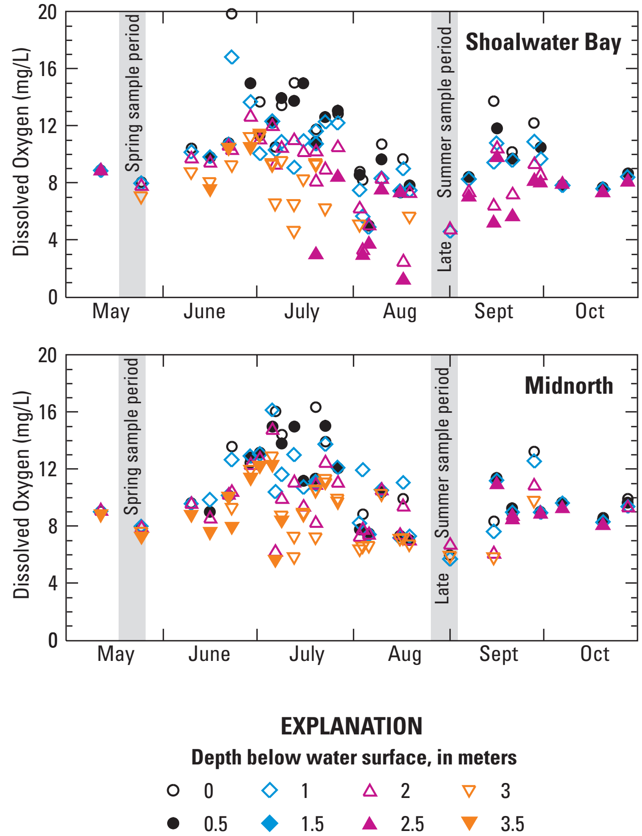

Figure 5. Depth-profile dissolved oxygen data at sampling sites Shoalwater Bay and Midnorth, Upper Klamath Lake, Oregon, May–October, 1999.

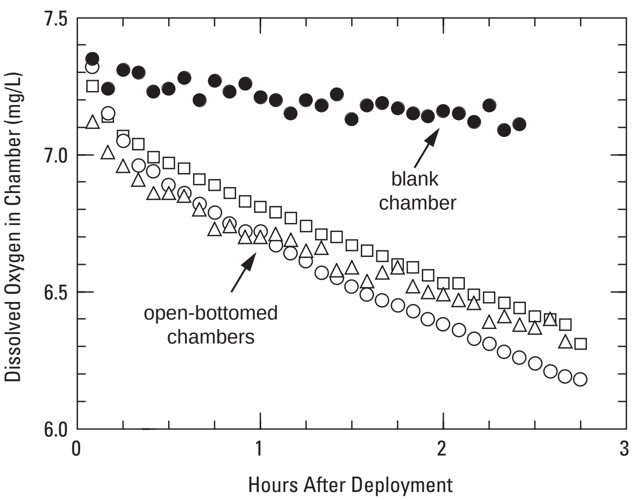

Figure 6. Data collected from sediment oxygen demand chambers deployed at sampling site Upper Midlake on May 27, 1999.

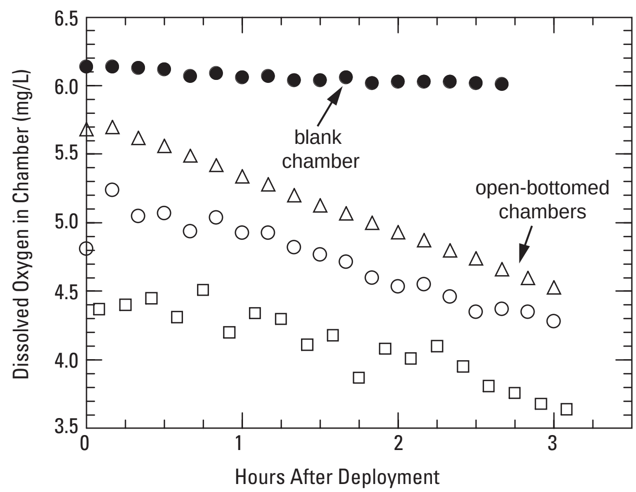

Figure 7. Data collected from sediment oxygen demand chambers deployed at sampling site Agency North on August 31, 1999.

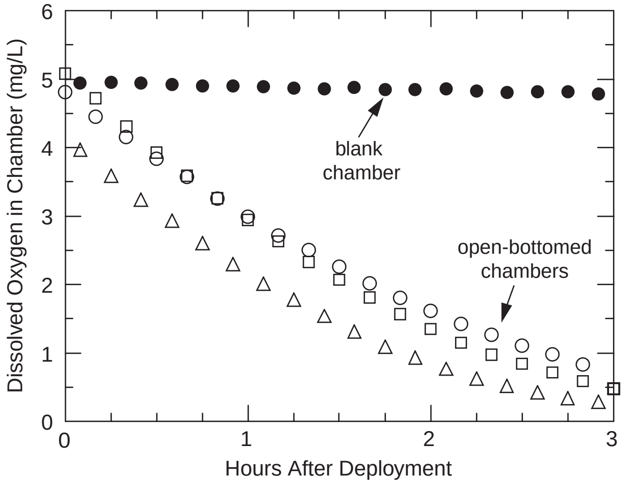

Figure 8. Data collected from sediment oxygen demand (SOD) chambers deployed at sampling site Ball Bay on August 26, 1999. [Solid symbols are values from the closed-bottomed ("blank") chamber used to measure water column demand, which was subtracted from values obtained from the open-bottomed chambers (open symbols) to obtain the SOD.]

75th percentile values of SOD_T being 1.1, 1.2, and 1.5 g/m^2/day, respectively, in the spring, and 1.4, 1.7, and 2.1 g/m^2/day in the late summer. The SOD varies over a relatively small range between about 1 and 3 g/m^2/day over most of the lake, and this does not change from spring to late summer (table 1).

The data from Ball Bay, however, indicate that significant small-scale exceptions can occur. While a good estimate of the oxygen demand at Ball Bay on August 26 could not be obtained, it was possible to conclude from the data that the oxygen demand was greater than 9 g/m^2/day, more than five times higher than the median of the values obtained over the rest of the lake (table 1). The quality of the data was good, and the blank indicated very little oxygen demand in the overlying water (fig. 8), leading to the conclusion that the sediments at the Ball Bay site were characterized during this time by an exceptional oxygen demanding capacity, when compared with the rest of the lake. The divers noted that the surface sediments were topped by a layer of particularly fluffy sediments perhaps an inch thick, while the water directly above the sediments was relatively clear. A feasible explanation for this phenomenon is that a patch of *A. flos-aquae* became trapped in the bay by the lake's circulatory pattern, and then sank to the bottom only a short time before the SOD experiments were attempted. A similar phenomenon might have been responsible for the near-zero dissolved oxygen concentrations measured at site WB in Howard Bay on August 30. It was impossible to measure SOD in Howard Bay at that time because there was not enough oxygen in the water column to allow the measurement of oxygen depletion over time; this lack of oxygen could have resulted after only a few days of an exceptionally high oxygen demand in the Howard Bay sediments.

Seasonal Differences in Sediment Oxygen Demand and Sediment Characteristics

In order to assess seasonal differences in SOD, the calculated, paired (spring/late summer) SOD_T values from each of the nine sites for which both values were obtained were tested for a difference in the central tendency of their distributions. This test yielded a significantly higher median lake SOD_T in the late summer than in the spring (median values 1.7 and 1.2 g/m^2/day, respectively). A statistically significant difference in the medians of SOD_{20} was not found, however; most of the seasonal dependence in SOD_T comes from spring to late summer differences in the water temperature. The same test was applied to OC, the percent fines, and RLOI. Of these, the only statistically significant seasonal difference was found in the percent fines (fig. 9), the content of the fines in the sediments being higher in the late summer than in the spring (median values 68% and 95% in the spring and fall, respectively). These data indicate that new surficial bottom sediment that settles in the late summer and fall (composed largely of detrital, filamentous algae) has a finer grain size distribution than the older (deposited primarily the previous summer and fall) surficial sediment in the spring.

Correlations with Sediment Characteristics

Correlations were calculated among the datasets SOD_{20}, OC, RLOI, and fine fraction. SOD_{20} values were used in order to remove the dependence on temperature before looking for correlations with other variables. All possible data pairs were included in the correlation, from both the spring and the late summer; therefore $n = 20$ for correlations involving SOD_{20} and $n = 22$ for all other correlations. The only significant correlation occurred between OC and RLOI (ρ=0.9, p<.001). Based on these correlations, it does not appear

Table 1. Spring (May 18–May 27, 1999) and late summer (August 24–September 1, 1999) values of sediment oxygen demand (SOD) in grams per square meter per day at ambient temperature (SOD_T), sediment oxygen demand at ambient temperature adjusted to 20 degrees Celsius (SOD_{20}), and bottom sediment laboratory data

[The indicated error bounds are +/- 1 standard deviation, based on a triplicate sample. When a range is given, only two values were available. When a single value is given, only one value was available. BB, Ball Bay; SB, Shoalwater Bay; WB, Wocus Bay; MN, Midnorth; UML, Upper Midlake; ML, Midlake; SP, Squaw Point; NBI, North Buck Island; PM, Pelican Marina; AN, Agency North; AS, Agency South; P50, median value; P75, 75th percentile value; P25, 25th percentile value; n, number of data values; ppt, parts per thousand]

Site or statistic	SOD_T (g/m²/day)		SOD_{20} (g/m²/day)		% Organic carbon		% Fines		Residue lost on ignition (ppt)	
	Spring	Late summer	Spring	Late summer	Spring	Late summer	Spring	Late summer	Spring	Late summer
BB	1.2 +/- 0.3	> 10.2*	1.5 +/- 0.3	> 9.6*	7.0 - 7.3	6.1 +/- 2.3	65.9 - 73.1	97.7 +/- 0.6	156 - 169	176 +/- 3
SB	1.0 +/- 0.1	1.5 +/- 0.4	1.2 +/- 0.1	1.7 +/- 0.4	7.4 +/- 0.2	7.2 +/- 0.5	66.8 +/- 14.6	95.2 +/- 0.6	193 +/- 5	180 +/- 4
WB	1.5 +/- 0.3	—**	2.1 +/- 0.4	—**	7.2 +/- 0.1	7.0 +/- 0.0	75.7 +/- 2.8	96.6 +/- 1.2	185 +/- 14	206 +/- 69
MN	1.7 +/- 0.3	1.6 +/- 0.2	2.2 +/- 0.5	1.5 +/- 0.2	6.1 +/- 0.1	5.9 +/- 0.5	67.1 +/- 2.3	97.7 +/- 0.5	149 +/- 13	154 +/- 4
UML	1.1 +/- 0.3	1.8 +/- 0.6	1.5 +/- 0.3	1.7 +/- 0.6	5.4 +/- 0.1	5.7 +/- 0.4	75.7 +/- 7.9	95.2 +/- 1.5	135 +/- 11	135 +/- 1
ML	0.6 +/- 0.1	1.2 +/- 0.1	0.9 +/- 0.1	1.3 +/- 0.2	3.8	4.8 +/- 2.2	39.9	86.5 +/- 3.0	100	103 +/- 7
SP	1.8 +/- 0.4	1.8 +/- 0.1	2.2 +/- 0.5	1.7 +/- 0.1	5.8 +/- 0.1	5.8 +/- 0.2	68.1 +/- 3.0	96.7 +/- 1.3	137 +/- 6	152 +/- 7
NBI	1.4 +/- 0.7	2.4 +/- 0.7	2.8 +/- 1.1	2.5 +/- 0.7	5.7 +/- 0.1	5.8 +/- 0.3	67.3 +/- 8.3	97.8 +/- 0.2	152 +/- 14	146 +/- 8
PM	—***	0.9 +/- 0.1	—***	1.9 +/- 0.1	6.0 +/- 0.1	5.9 +/- 0.2	79.8 +/- 3.9	95.2 +/- 1.7	157 +/- 13	149 +/- 5
AN	1.1 +/- 0.1	1.7 +/- 0.3	1.6 +/- 0.2	1.9 +/- 0.4	10.6 +/- 1.3	8.3 +/- 0.3	63.5 +/- 8.2	92.2 +/- 4.8	217 +/- 18	170 +/- 5
AS	1.3 +/- 0.1	3.2 +/- 0.8	1.5 +/- 0.1	3.6 +/- 0.9	10.2 - 10.4	26.3 +/- 4.1	88.8 - 90.4	92.6 +/- 0.2	182 - 184	536 +/- 46
P50	1.2	1.7	1.6	1.7	6.1	5.9	68.1	95.2	157	154
P75	1.5	2.1	2.2	2.2	7.4	7.2	75.7	97.7	185	180
P25	1.1	1.4	1.4	1.6	5.7	5.8	66.8	92.6	137	146
n	10	9	10	9	11	11	11	11	11	11

* Loss of dissolved oxygen was rapid and nonlinear; a good estimate of SOD could not be made (value not included in statistics).
** Not enough oxygen at this site to make a measurement.
*** Pump was not operating at optimum speed; data are not intercomparable.

Table 2. Literature values of sediment oxygen demand measured by *in-situ* techniques.
[OC, organic carbon; g/m^2/day, grams per square meter per day]

Location	Description	SOD_{20}, in g/m^2/day	Reference
Willamette River, Oregon	silty sediment, moderate organic content (1–10% OC)	1.3–4.1	Caldwell and Doyle, 1995
Tualatin River, Oregon	slow-moving, reservoir reach, silty sediment, moderate organic content	0.6–4.4	Rounds and Doyle, 1997
Tennessee-Tombigbee Waterway, Mississippi	measurements represent a range of bottom characteristics along the waterway	0.4–1.2	Truax et al., 1995
Five Southwestern Lakes	trophic states varied from oligotrophic to eutrophic	0.3–9.0	Veenstra and Nolen, 1991

that SOD can be determined from any of these sediment characteristics. Future attempts to correlate SOD with sediment characteristics should perhaps focus on nutrient content, particularly the carbon to nitrogen or carbon to phosphorus ratios, as a measure of how readily the organic matter in the sediments is metabolized.

Effects of Current Velocity on Sediment Oxygen Demand

Several researchers have noted that SOD increases with near-bottom water velocity, up to the point at which the SOD is no longer limited by the rate of transfer of dissolved oxygen to the sediments through the diffusive boundary layer (Whittemore, 1986; Josiam and Stefan, 1999; Mackenthun and Stefan, 1998; Boynton et al., 1981). This relationship also can be predicted on theoretical grounds (Nakamura and Stefan, 1994). By using enclosed chambers to perform these SOD experiments, the variation associated with different current velocities at each site is removed, and measurements are collected under the same current velocity conditions and are therefore intercomparable. These SOD values, while intercomparable, may vary *in situ* with environmental conditions and, in particular, with current velocities that are largely determined by a combination of lake level and wind conditions.

Dye studies in the chambers that were used in this study have shown that the mean advective velocities

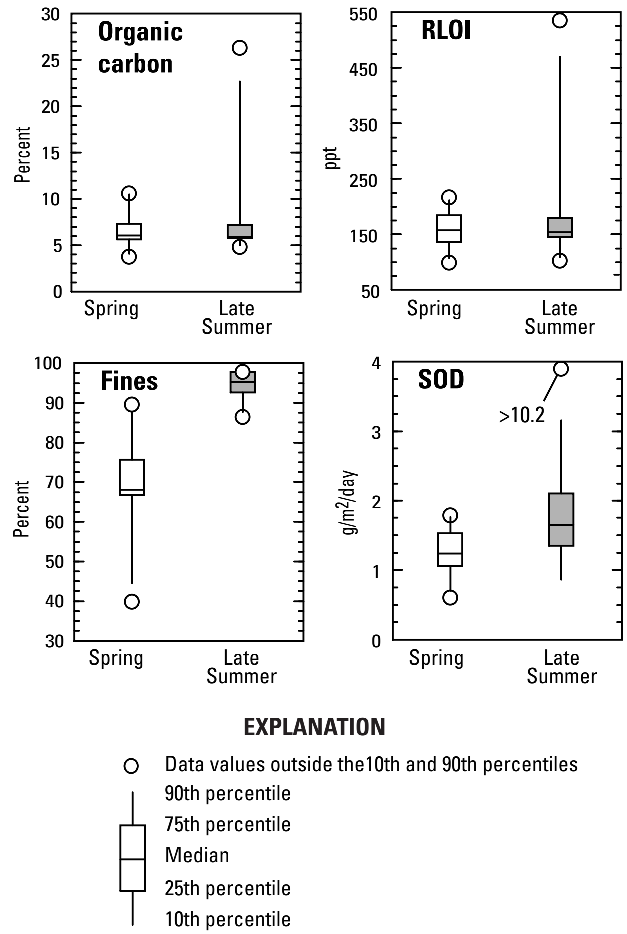

Figure 9. Spring (May 18–May 27, 1999) and late summer (August 24–September 1, 1999) distributions of SOD_T (sediment oxygen demand at temperature T, not corrected to 20^{o}C [degrees Celsius]) and sediment characteristics. [N=10 for SOD_T; N=11 for all other variables. RLOI= residue lost on ignition; ppt=parts per thousand.]

inside the chambers vary from approximately zero at the center of the chamber to approximately 6 cm/s at the outside perimeter when the recirculating pump is operating at optimum speed, with an areally weighted average of about 3.2 cm/s (M.C. Doyle, USGS, unpub. data). Because there has been no investigation of the currents and velocity profiles in the lake, there are no data that can be used to relate a near-bottom velocity to velocities nearer the surface, or to determine its frequency of occurrence. Should such data become available in the future, the following discussion may prove useful in evaluating the SOD collected in this study in the context of "average" or "extreme" velocity conditions at a particular site.

A semiquantitative estimate of how much the SOD varied with near-bottom water velocity was obtained from two experiments that were performed to examine the effect of changing the pump speed (and therefore the recirculation velocity inside the chamber). During the first experiment, at Squaw Point on August 27, data were first collected routinely with the pump set to optimum speed for 2 hours and 45 minutes, which yielded an average SOD_{20} for the site of 1.7 +/-0.1 g/m^2/day. At the end of that time, the pump speed was changed to maximum capacity and data were collected for another 2 hours, which yielded an average SOD_{20} of 3.7 +/-1.4 g/m^2/day. At the maximum pump speed, the areally weighted velocities inside the chamber are close to 6.6 cm/s, as determined by dye experiments (M.C. Doyle, USGS, unpub. data). Approximating a linear rate of change over this range in velocity, the change of SOD_{20} with change in velocity (ΔSOD/ΔV) would be about 0.6 g/m^2/day per cm/s.

The second experiment, at Shoalwater Bay on September 1, was designed to test for a difference in the SOD rate at a pump speed set lower than the optimum setting. Data were collected routinely for 3 hours, which yielded an average SOD_{20} of 1.7 +/-0.4 g/m^2/day. Then the pump was turned to 40% of maximum capacity, and data were collected for 1.5 hours, which yielded an average SOD_{20} of 1.1 +/-0.1 g/m^2/day, giving ΔSOD/ΔV= 0.4 g/m^2/day per cm/s.

These are very rough estimates of the way that SOD varies with current velocity in Upper Klamath Lake, but they are reasonable and consistent with what has been found elsewhere. For example, Jorgensen and Des Marais (1990) found an increase in SOD from 1.8 to 4.3 g/m^2/day over the velocity range 0.3 to 7.7 cm/s (velocities were measured 1 cm above the sediments). This corresponds to ΔSOD/ΔV= 0.3 g/m^2/day per cm/s. Mackenthun and Stefan (1998) calculated values of ΔSOD/ΔV of 0.2 g/m^2/day per cm/s for one type of lake sediment, and 1.1–1.7 g/m^2/day per cm/s for a second type of lake sediment, over a change in velocity from 0.7 to 10 cm/s. Over the range from 5 to 10 cm/s, Boynton et al. (1981) found ΔSOD/ΔV= 0.3 g/m^2/day per cm/s over a muddy bottom. The change in SOD with velocity should be determined *in situ* for the particular sediments under investigation, because the values are site-specific. For example, during a study using the same chambers used in this study in the Tualatin River, Oregon, no change in SOD was observed when the pump speed was changed from 40% to 60% capacity (M.C. Doyle, USGS, unpub. data).

The theory of transport through the boundary layer predicts that the dependence of SOD on velocity will decrease with increasing velocity until, at some point, the metabolic reactions within the sediments are not limited by the rate of transfer of dissolved oxygen through the boundary layer to the sediment/water interface. At that point, SOD becomes independent of velocity. As current velocities continue to increase, they become strong enough to resuspend sediments. The velocity at which sediments are resuspended is associated with an increase in the oxygen demand measured with the chambers. Whether the oxygen demand measured by the chambers at that point can be correctly termed “SOD” is debatable, but the increase in the oxygen demand near the sediment/water interface is real and reflects a process that occurs in the lake. In Upper Klamath Lake, where the top several centimeters of the sediments can be unconsolidated and particularly fine, these two current regimes probably merge. The change in the SOD measured between operating the chamber pumps at minimum and optimal capacity is largely a reflection of increased transport through the boundary layer, but the change in SOD measured between operating the chamber pumps at optimal and maximum capacity may well be largely due to the resuspension of sediments. Operationally, it is not as important to be able to distinguish between the two mechanisms as it is to recognize the relation between SOD and currents. This relation also implies that high-wind events in the lake could have serious and episodic implications for water quality, if a large mass of sediments with high oxygen-demanding capacity are lifted into the water column by strong currents.

Effects of Sediment Oxygen Demand on Water Quality

As a means of evaluating the relative importance of SOD in controlling the dissolved oxygen concentration in the lake, the uncorrected SOD values were used, with the depth and temperature at the site and time that the measurements were taken, to calculate a theoretical reduction in dissolved oxygen concentration over a 24-hour period (table 3). The calculated changes that could be attributed to SOD over that time frame are, in general, less than 1 mg/L, and were higher at each site in the fall than in the summer because of the higher temperatures and smaller depths.

Continuous dissolved oxygen data were available for approximately 2-week periods surrounding the fall sampling dates at three sites: Midnorth, Shoalwater Bay, and Ball Bay. With these data, the change in dissolved oxygen at each point in the continuous dataset

Table 3. Potential reduction in dissolved oxygen concentration in 24 hours that could be attributed to measured sediment oxygen demand

[T, temperature; Δ, reduction in dissolved oxygen concentration; *, estimated depth; m, meter; T, temperature; °C, degrees Celsius; mg/L, milligrams per liter]

	SPRING May 18–May 27, 1999			LATE SUMMER August 24–September 1, 1999		
Site	Depth (m)	T (°C)	Δ (mg/L)	Depth (m)	T (°C)	Δ (mg/L)
BB	3.4	16.4	0.4	2.8	20.9	>3.7
SB	3.1	15.9	.3	2.5	17.5	.6
WB	2.4	14.4	.6	1.7	—	—
MN	3.7	15.6	.5	3.1	21.0	.5
UML	3.0*	16.0	.4	2.4*	20.4	.7
ML	3.8	14.6	.2	3.1	19.7	.4
SP	2.9	16.9	.6	2.1	21.1	.9
NBI	2.5	12.7	.6	1.9	19.7	1.3
PM	2.7	13.4	—	2.1	19.9	.9
AN	2.8	14.1	.4	2.2	17.6	.8
AS	2.1	17.1	.6	1.5	17.8	2.1

relative to the concentration 24 hours earlier was calculated (fig. 10). The changes in dissolved oxygen over a 24-hour period at these sites cycle between positive and negative values on a time scale of from 2 to several days. In general, the changes are of a magnitude that would dominate the changes attributable to SOD alone, although the latter would be significant, not negligible, in comparison. The processes responsible for these changes are the other components of the oxygen budget—primarily algal photosynthesis and respiration, reaeration, and advection. These data were collected at mid-water column, so to the extent that there is any stratification, the dissolved oxygen at mid-water column will not necessarily mimic the dissolved oxygen at near-bottom. The period from mid-August to mid-September, however, is probably characterized by very little stratification, as was noted previously.

At Ball Bay, where the SOD was anomalously high in comparison to the rest of the lake, the continuous data shows a declining trend in the dissolved oxygen concentration over the 10 days prior to the sampling date and a large 24-hour reduction in dissolved oxygen about 2 days prior. These aspects of the data could be explained by diminished algal metabolic activity enhanced by an episode of very high but localized SOD.

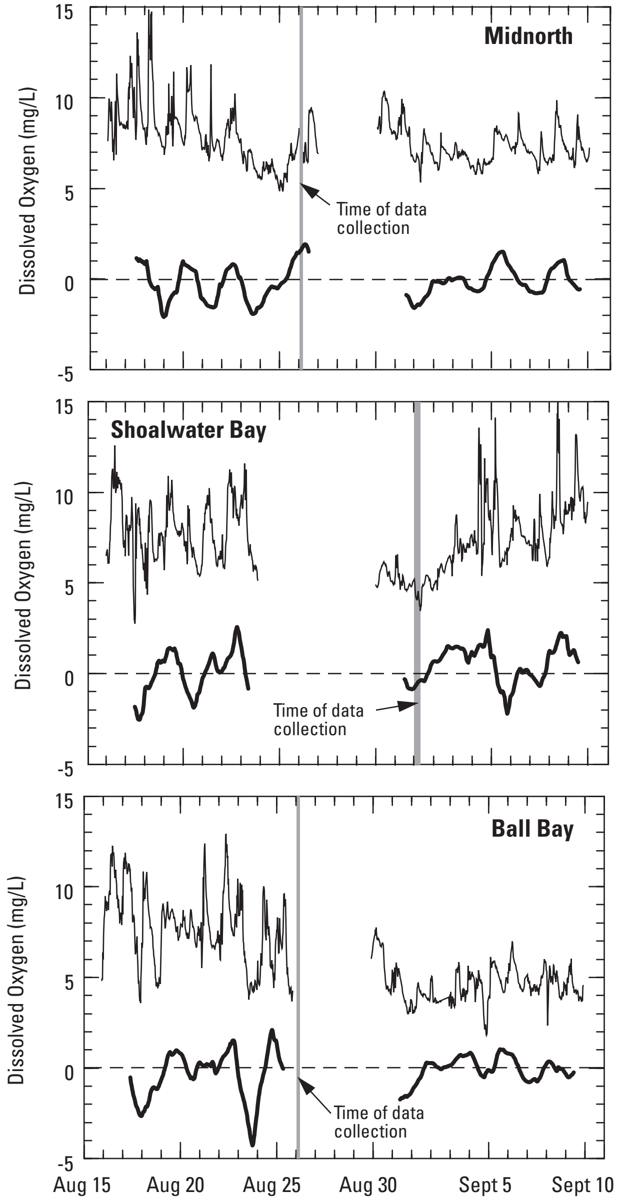

Figure 10. Continuous dissolved oxygen concentration data collected in late August and early September, 1999 at sampling site Ball Bay, Shoalwater Bay, and Midnorth in Upper Klamath Lake, Oregon. Also shown is the change in dissolved oxygen concentration from 24 hours previous, smoothed with a 24-hour running average.

At the time of the late summer sampling, the algal bloom had not undergone its final decline of the year, and algal metabolic activity continued, though at reduced levels compared to earlier in the summer. The effect of SOD on dissolved oxygen concentrations would be much more pronounced during September and October, therefore, especially if water temperatures remain relatively high, as photosynthetic production greatly diminishes but SOD remains at levels close to those presented in this report.

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U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the
BUREAU OF RECLAMATION

Sediment Oxygen Demand in Upper Klamath and Agency Lakes, Oregon, 1999

Water-Resources Investigations Report 01–4080

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Upper photographs:

Sediment oxygen demand chamber on boat and being deployed.

Lower photograph:

Divers examine sediment core samples.