USGS
science for a changing world

Prepared in Cooperation with the Bureau of Reclamation

Sediment Oxygen Demand in Lake Ewauna and the Klamath River, Oregon, June 2003

Scientific Investigations Report 2005–5228

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

Front cover:
Right, view of Klamath River looking downstream, with railroad overpass in the foreground, near river mile 251.
Left, view from the east of the Link River, showing the Highway 39/140 overpass and the upper portion of Lake Ewuana.
Photographs by Dennis D. Lynch (U.S. Geological Survey).

Sediment Oxygen Demand in Lake Ewauna and the Klamath River, Oregon, June 2003

By Micelis C. Doyle and Dennis D. Lynch

Prepared in cooperation with the Bureau of Reclamation

Scientific Investigations Report 2005–5228

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

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2005

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Doyle, M.C., and Lynch, D.D., 2005, Sediment oxygen demand in Lake Ewauna and the Klamath River, Oregon, June 2003: U.S. Geological Survey Scientific Investigations Report 2005–5228, 14 p.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
centimeter (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
square meter (m^2)	10.76	square foot (ft^2)
liter (L)	1.057	quart (qt)
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8×°C)+32

Sediment Oxygen Demand in Lake Ewauna and the Klamath River, Oregon, June 2003

By Micelis C. Doyle and Dennis D. Lynch

Abstract

Sediment oxygen demand (SOD) is the rate at which dissolved oxygen is removed from the water column during the decomposition of organic matter in streambed or lakebed sediments. In lakes and slow moving rivers, or rivers with high levels of organic matter in the bed sediment, SOD can be a major cause of low dissolved oxygen (DO) concentrations in the water column. Low DO concentrations can be detrimental to fish and other aquatic life in a stream or lake.

In June 2003, replicate SOD measurements were made at one site in Lake Ewauna and three sites in the Klamath River above Keno Dam. Individual measurements of SOD_{20} rates (temperature corrected to 20 degrees Celsius) ranged from 0.3 to 2.9 g O_2/m^2/day (grams of oxygen per square meter per day), with a median value of 1.8 g O_2/m^2/day (n=22). The variability of individual SOD measurements at a site was equal to or greater than the variability of SOD rates among the four sites. Consequently, the overall median SOD for the entire study reach should be used in water-quality models. SOD values measured in this study are about 10 times smaller than estimates made in this study area by the Oregon Department of Environmental Quality in 1994. The rates measured in the Klamath River are similar to SOD rates measured several miles upstream in Upper Klamath Lake in 1999. These two findings indicate that the unusually high SOD rates in the Klamath River result from causes other than the presence of large amounts of woody debris in bottom sediments from past and ongoing sawmill operations, which has been suggested by other investigators.

An areal rate of water-column oxygen demand was estimated from control chambers during the study. In early June 2003, the median rate was 3.8 g O_2/m^2/day, which was more than double the SOD_{20} rate. Taken together, the SOD and water-column oxygen demand can more than account for the severe hypoxia that develops in this reach of the Klamath River from July into October. The largest source of labile organic matter contributing to this hypoxia likely comes from algal blooms in Upper Klamath Lake.

Bed-sediment samples were collected and correlations were considered between SOD_{20} rate and percentage of organic material, and SOD_{20} rate and percentage of sediment finer than 63 microns. Based on these correlations, it does not appear that SOD variability can be readily determined from these two sediment characteristics.

Introduction

Background

Low dissolved oxygen (DO) levels have been observed in Lake Ewauna and the Klamath River, Oregon. Continuous data collected in 2003 (Jason Cameron, Bureau of Reclamation, written commun., 2005) show DO concentrations below 4 mg/L (milligrams per liter) for many weeks in the summer and early fall, and there are many days when DO concentrations are less than 1 mg/L (fig. 1). These low DO levels can be detrimental to the survival of fish, including two endangered sucker species, and other aquatic organisms. Low DO conditions are associated with warm water temperatures and the development of large algal blooms in Upper Klamath Lake, located just upstream. Transport of labile algal organic matter from Upper Klamath Lake into Lake Ewauna and the Klamath River above Keno Dam (fig. 2) contributes to periods of hypoxia that extends throughout the water column. Low DO levels in Lake Ewauna and the Klamath River have also been attributed to high oxygen demand from streambed sediments (sediment oxygen demand, or SOD) (CH2M Hill and Wells, 1995). Mayer (2001) hypothesized that the high SOD levels may be caused by releases from Upper Klamath Lake high in organic matter, and by accumulated bark and woody debris on the channel bottom from past and ongoing practices of transporting and storing logs on the Klamath River.

In August 1994, the Oregon Department of Environmental Quality (ODEQ) attempted a few SOD measurements in Lake Ewauna (Klamath River mile [RM] 252.3) and in the Klamath River (RMs 249.4 and 239.3), downstream from Upper Klamath Lake (CH2M Hill and Wells, 1995). In this river reach, ODEQ experienced difficulty in making SOD measurements due to the soft bottom sediments that allowed the SOD chambers to sink into the riverbed. The few data that were collected, however, suggested that SOD levels in Lake Ewauna and the Klamath River could be as much as 10 times larger than levels measured by USGS in Upper Klamath Lake in 1999 (Wood, 2001).

Water-quality management agencies are attempting to quantify the mechanisms that influence DO concentrations in the Klamath River from Lake Ewauna to Keno Dam (fig. 2). Photosynthetic production, biochemical oxygen demand (BOD), reaeration, and sediment oxygen demand (SOD) are

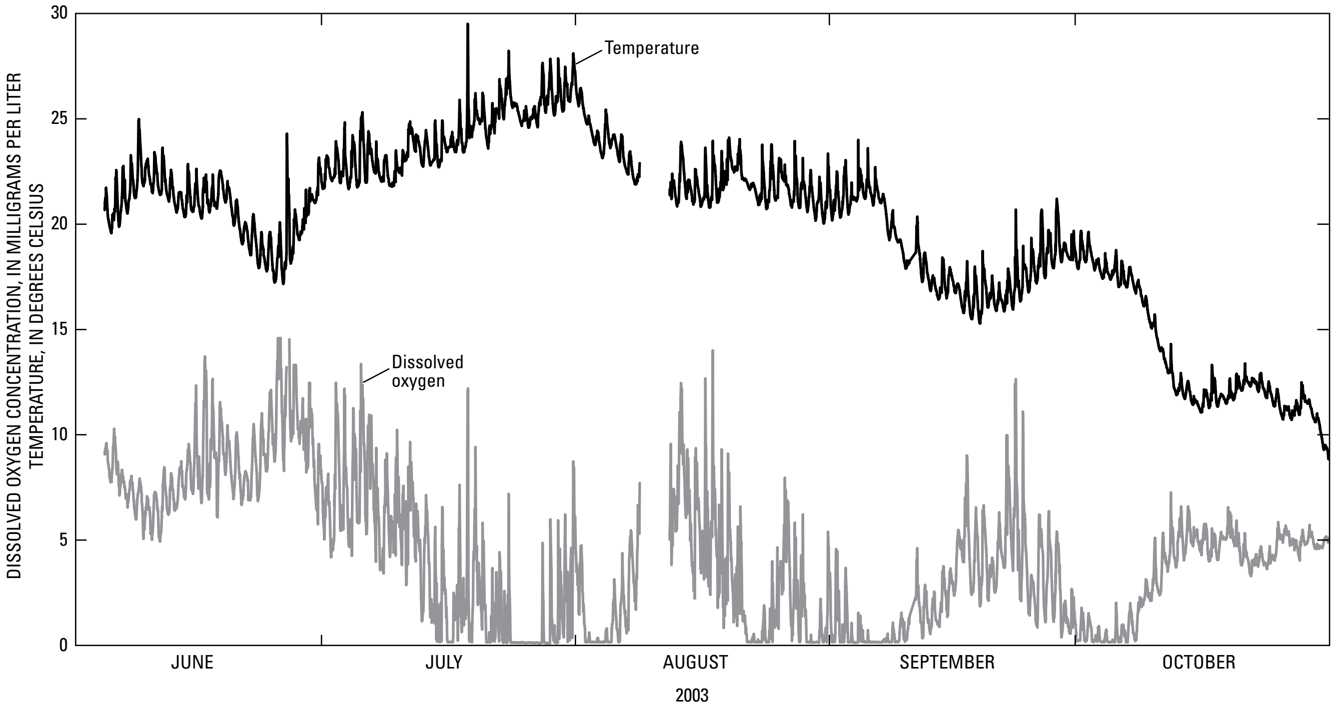

Figure 1. Daily averages of water temperature and dissolved oxygen concentrations 1 meter below water surface at river mile 246 for the period June–November 2003.

all important components of the total DO budget. SOD is the rate at which DO is removed from the water column at or near the sediment-water interface. SOD can be attributed to two distinct processes: (1) oxygen consumption through biological activity in the sediments and (2) oxygen consumption resulting from chemical oxidation of reduced chemical species. In lakes and slow moving rivers with high levels of organic matter in the bed sediment, SOD can be a major cause of low DO concentrations in the water column (Porcella and others, 1986; Kelly, 1997; Rounds and others, 1999). This study, done in cooperation with the Bureau of Reclamation (BOR), attempts to quantify the SOD portion of the oxygen budget for Lake Ewauna and the Klamath River above Keno Dam.

Purpose and Scope

This report discusses the USGS measurements of SOD in Lake Ewauna and the Klamath River above Keno Dam, done in cooperation with the BOR. Specifically, the investigation was designed to:

- Determine the magnitude and spatial variability of SOD from Lake Ewauna to the Klamath River above Keno Dam.
- Assess whether SOD varies at different points in the cross-section and with river depth.
- Assess associations between SOD and bed-sediment particle size and organic carbon content.
- Obtain accurate SOD data to help quantify the oxygen budget in this stretch of the Klamath River and to improve water-quality models being developed by other agencies and consultants.
- Compare SOD rates in this river reach to rates measured earlier by ODEQ in 1994 and rates measured in Upper Klamath Lake in 1999 (Wood, 2001).

This report is intended for use by resource managers and regulatory agencies as they strive to make the Klamath River suitable for aquatic life. It is also intended for use by researchers and modelers who are interested in the dynamics of DO in aquatic ecosystems and the successful collection and incorporation of SOD data into water-quality studies. Management and regulatory agencies (including the Bureau of Reclamation, Oregon Department of Environmental Quality, and U.S. Environmental Protection Agency) may use results from this study to guide the development of Total Maximum Daily Loads for oxygen demanding substances in Lake Ewauna and the Klamath River upstream of Keno Dam.

Acknowledgements

The authors express gratitude to the following people and organizations: Michael Berg and Jason Cameron of the

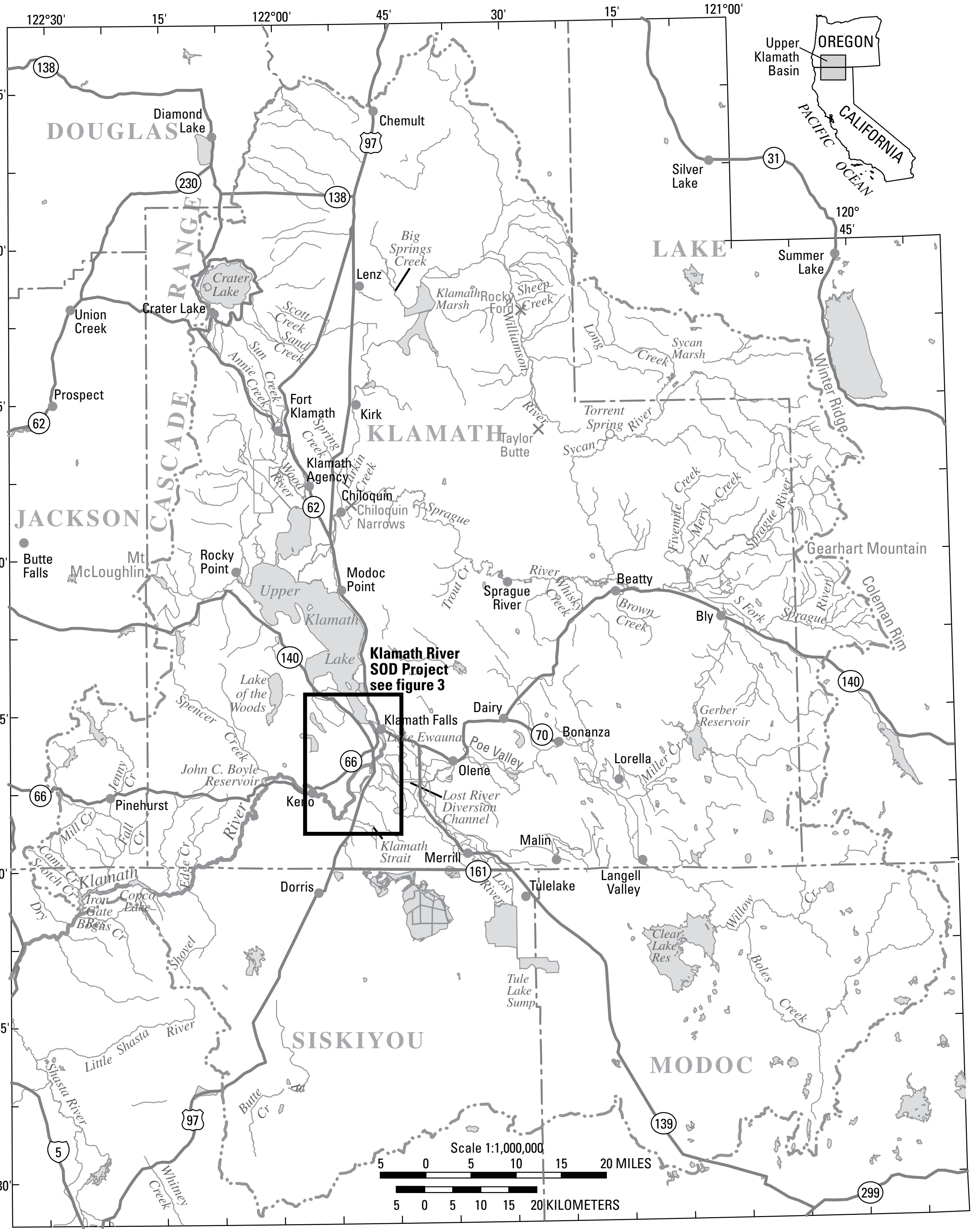

Figure 2. The Klamath Basin, showing study area.

Bureau of Reclamation for their assistance in data collection and the operation of a continuous water-quality monitor, Stewart Rounds for his technical assistance in data analysis, Ken Skach, who served as one of the SCUBA divers, and Rip Shively and his staff at the USGS Klamath Falls Field Station for the use of their boats and other equipment during the fieldwork portion of this study.

Study Area

The headwaters of the Klamath River begin near the outflow from Upper Klamath Lake in Klamath Falls, Oregon, at the Link River Dam. Here, some flow is diverted for irrigation by the Bureau of Reclamation Klamath Project. The remainder is either spilled over the dam or used for power generation. The water that flows through Lake Ewauna, and subsequently the Klamath River, meanders for about 405 kilometers southwesterly through the Cascade Range in southwestern Oregon and northwestern California and into the Pacific Ocean (fig. 2). This study focused on the upper section of the Klamath River from Lake Ewauna to the Keno Dam (fig. 3). Figure 3 shows the general location of the SOD deployment sites at river miles (RM) 252.3, 249.4, 244.2, and 239.3, and the location of the Bureau of Reclamation's water-quality monitor.

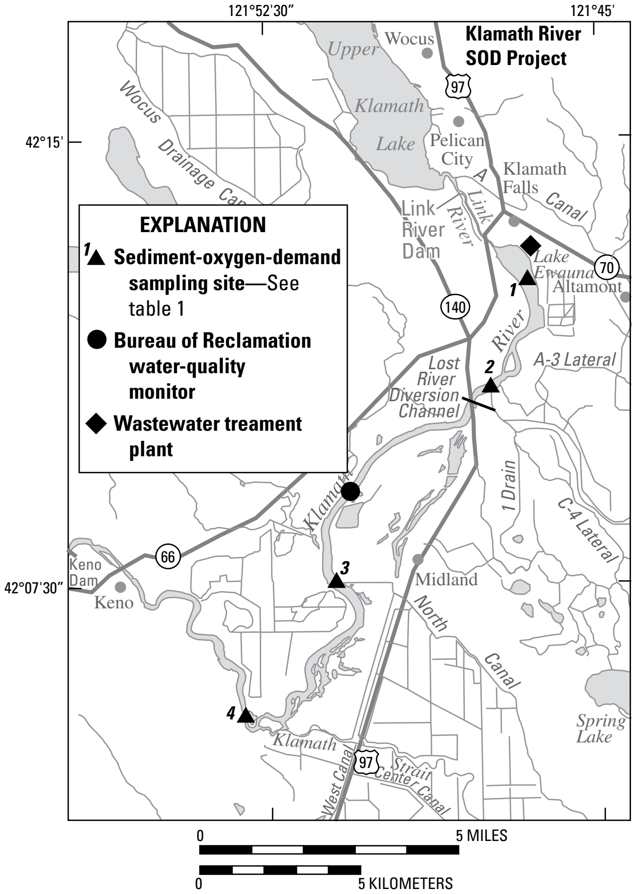

Figure 3. Study area and sediment oxygen demand measuring sites, Lake Ewauna, the Klamath River, and the location of the continuous water-quality monitor at river mile 246.

The drainage area upstream of the study location encompasses about 10,100 square kilometers. Annual precipitation in the study area, at Klamath Falls, Oregon, averaged 34 centimeters for the period 1902–1996 (Risley and Laenen, 1999). The study reach is slow moving and has mid-channel depths ranging from about 2.5 to 6 meters, a channel width that averages about 200 meters, and a mantle of soft, fine-grained, organic bottom sediment that contains bark and other woody debris over large areas, as a result of the transportation and storage of logs on the Klamath River. During periods of base flow (June through October), this reach of the Klamath River behaves more like a reservoir than a free-flowing stream, experiencing periods of thermal stratification and low DO concentrations near the river bottom. For example, based on channel bathymetry and average streamflow conditions, the estimated time of travel through the 32 kilometer study reach is about 8 to 10 days in July, or about 4.3 centimeters per second.

Methods and Procedures

Study Design

Site selection was designed to obtain representative SOD measurements from the Klamath River while maintaining spatial coverage of the study area. Chamber deployment locations were selected based on results from a field reconnaissance in August 2001 and a desire to obtain SOD measurements in the same general location as those attempted by ODEQ in 1994. Field reconnaissance of the study area involved measuring field parameters, inspecting bottom-sediment samples, and documenting the location of each potential chamber deployment site using a global positioning system device.

Samples of bottom sediment were obtained using a Petite-Ponar dredge sampler. Each bottom-sediment sample was physically inspected for color, odor, and grain size (sand, silt, or clay) to determine the variability and frequency of sediment types in the study area. Measurements of water temperature, specific conductance, pH, depth, and DO were taken near the river surface, approximately mid-depth, and near the river bottom using a multiparameter water-quality instrument.

DO concentrations near the river bottom in the study area during site reconnaissance in August 2001 were in most cases less than 0.5 mg/L (milligrams per liter). These hypoxic conditions were unsuitable for obtaining SOD measurements using our established protocols. To successfully measure SOD, there must be sufficient oxygen in the water column (> 3.0 mg/L) near the river bottom so that DO depletion in the SOD chambers can be observed before microorganisms at the sediment surface become oxygen limited. Above 3.0 mg/L, oxygen-depletion rates are generally linear; below 3.0 mg/L, oxygen-depletion rates become nonlinear, trailing off to near zero as DO concentrations approach 0 mg/L. Therefore, it was determined that SOD chambers would be deployed just prior to the time of the year when this section of the Klamath River experiences hypoxic conditions, namely in early June. Data shown in figure 1 confirm that low DO concentrations could make SOD measurements difficult using our protocols and criteria during the summer and early fall.

Sediment Oxygen Demand Chambers

The chambers used in this study (fig. 4A and 4B), the procedures for their deployment, and the collection of the data have been described in detail elsewhere (Rounds and Doyle, 1997; Wood, 2001; Doyle and Rounds, 2003). The chambers are based on an original design by Murphy and Hicks (1986). They are open-bottomed opaque plastic cylinders that isolate a known volume of water (52 liters) over a known area of bottom sediment (0.225 m^2), with a multiparameter water-quality monitoring instrument mounted vertically in the center of the chamber. The water-quality monitoring instrument logs measurements of temperature, DO, conductivity, turbidity, and pH. Each chamber was equipped with a rheostat that controlled the pump speed and consequently the circulation velocity within the chamber. The lower part of the chamber has a stainless steel collar to assist in bed sediment penetration and also to provide a good seal to the river bottom when seating the chambers (fig. 4A). Due to the very soft bottom sediments, a circular hole large enough for the stainless-steel collar to fit through was cut into a 1-m^2 piece of 6.3 millimeter polypropylene plastic that was used as a seating platform for each chamber. The additional surface area provided by the platform prevented the chambers from sinking into the sediments beyond the design point. This is the same platform design used in the SOD study on Upper Klamath Lake (Wood, 2001).

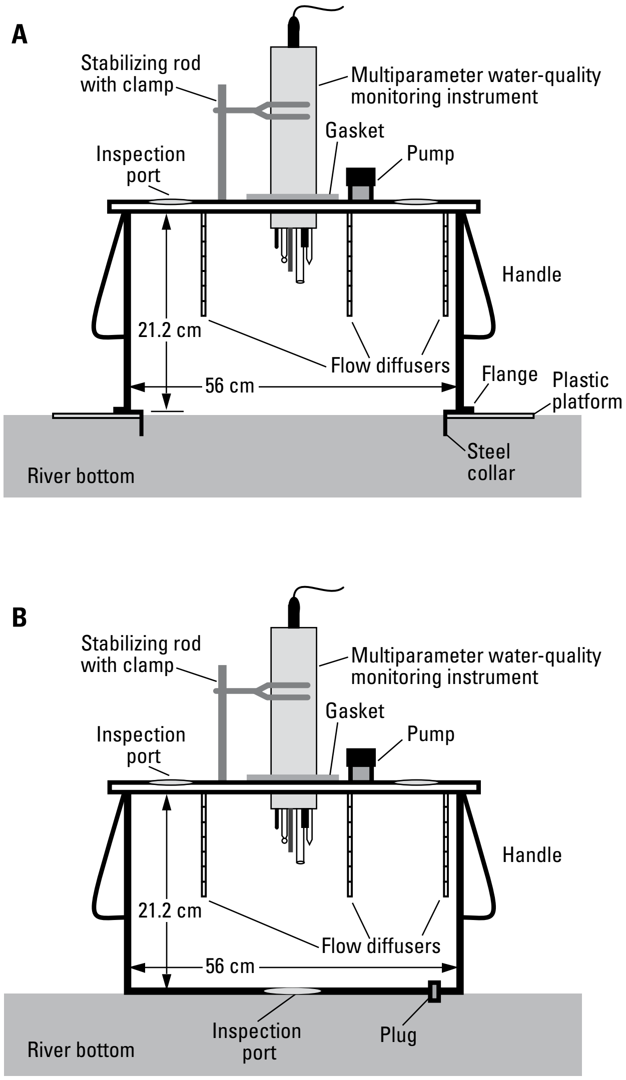

Figure 4. Diagram of (A) sediment oxygen demand measurement chamber and (B) control chamber.

Sediment Oxygen Demand Chamber Deployment

SOD chamber deployments were performed in triplicate with the general objective of obtaining an average SOD rate for each site. Efforts were made to obtain measurements across the cross-section at each deployment site. Virtually every location selected for an individual SOD measurement had soft, muddy bottom sediment where the chamber could be easily seated. In addition, at nearly all selected locations (according to SCUBA divers on the project) the chamber practically seated itself, in that very little or no force was applied to push the chamber into the bottom sediments. The chambers were seated up to the top of the stainless-steel collar seen in figure 4A. If not for the seating platform, the chambers would have sunk too deeply into the sediments and an accurate SOD measurement could not have been obtained.

The chambers were lowered and carefully seated onto the bottom sediments by SCUBA divers. Every effort was made to minimize the disturbance of the bottom sediments within the SOD chambers. As an extra precaution after deployment, each SOD chamber sat undisturbed on the bottom for 15 minutes to allow any resuspended sediment to settle. After the settling period, the valves on the chambers were directed to purge water from inside the chamber for at least 15 minutes (a time period sufficient to flush at least two chamber volumes) in order to fill the chamber with water from the surrounding near-bottom environment through the large inspection ports. After purging, SCUBA divers redirected the valves to recirculate water inside of the chamber and the large inspection ports were closed. After closing the inspection ports, the DO concentration in the chamber was recorded at 10-minute intervals for 2 to 3 hours. A minimum of three SOD chamber deployments were attempted at each site or river cross section to provide an assessment of spatial variability, and to evaluate potential associations with river depth and sediment characteristics.

A single “control” chamber (fig. 4B) was deployed at each site concurrently with the three SOD chambers to measure the oxygen demand associated only with the water overlying the bottom sediments. The control chamber is designed essentially the same as the SOD chambers except that the bottom is covered with polypropylene plastic, thereby isolating water in the chamber from the bottom sediments.

Oxygen demand measured in the control chambers was subtracted from the oxygen demand measured in the open-bottomed chambers at each deployment site in order to calculate oxygen demand solely from bottom sediments. The procedure for deploying and collecting data from the control chamber was the same as for the open-bottomed chamber.

Calculation of Sediment Oxygen Demand

Methods used to calculate SOD in this study were similar to those used in other USGS SOD studies (Rounds and Doyle, 1997; Wood, 2001). The change in oxygen concentration in the chamber with time is typically linear after an initial stabilization period, usually lasting less than 20 minutes (fig. 5). On occasion there was an initial nonlinear change in DO that is attributable to the suspension of sediment during the deployment and purging of the chambers. This sediment tends to settle back to the bottom within the first several minutes after the inspection ports are closed (Caldwell and Doyle, 1995, p. 8). In cases when this was observed, the early, nonlinear data were not included in the time series analysis.

The SOD rate is calculated from a graph of DO concentration in the chamber versus time (fig. 5). The slope of the oxygen depletion line is determined through linear regression. The following equation is used to calculate the SOD rate:

$$SOD_T = 0.024\frac{V}{A}(-b) \tag{1}$$

where SOD_T is the sediment oxygen demand rate in grams of oxygen per square meter per day (g O_2/m^2/day) at water temperature T, b is the slope of dissolved oxygen concentration with time in milligrams per liter per hour (after subtracting the slope measured in the control chamber), V is the volume of the chamber in liters, A is the area of bottom sediment covered by the chamber in square meters, and 0.024 is a units-conversion constant.

Measured SOD rates were corrected to 20 degrees Celsius using a Q10 (or Van’t Hoff) equation:

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

where SOD_{20} is the SOD rate at 20 degrees Celsius, and T is the water temperature during measurement in degrees Celsius (Thomann and Mueller, 1987). This correction does not hold for temperatures less than 10 degrees Celsius; however, water temperatures exceeded 10 degrees Celsius at all times during this study. The SOD_{20} value is useful when comparing SOD rates obtained at different temperatures.

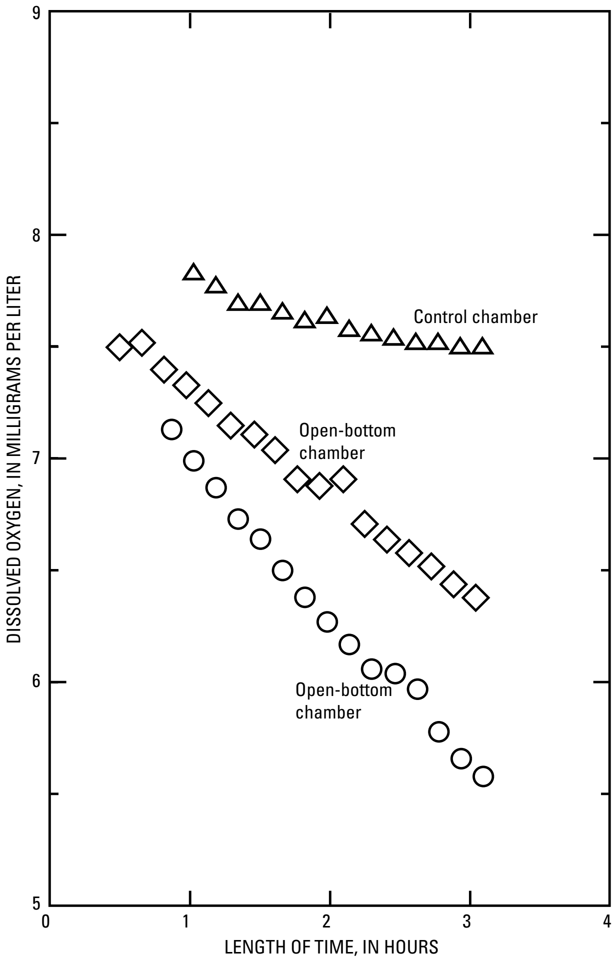

Figure 5. Dissolved oxygen depletion curves from data collected from two sediment oxygen demand chambers and a control chamber at river mile 249.4 in the Klamath River.

Sediment Sample Collection and Analysis

SCUBA divers collected bottom-sediment samples adjacent to each SOD chamber (excluding the control chamber) using a cylindrical polycarbonate tube that was carefully pushed into the bottom sediment next to each chamber. The upper 15–20 centimeters of the bottom material was subsampled for analysis, homogenized, and sent to the USGS Sediment Laboratory at the Cascade Volcano Observatory (CVO) in Vancouver, Washington. Sediment samples were analyzed for percent finer than 63 microns (Guy, 1969) and percent organic matter (Fishman and Friedman, 1989).

Quality Assurance of Data

Assessment of Data Collected from Sediment Oxygen Demand and Control Chambers

The quality of the data collected during the fieldwork portion of this study was determined by (1) inspecting the physical integrity of each chamber after deployment, (2) comparing the turbidity of water inside and outside each chamber to ensure that bottom sediment was not significantly resuspended before or during the SOD measurement, and (3) evaluating the oxygen-depletion curves to ensure they were linear and without discontinuities. During physical inspection after deployment, all components and chamber settings were evaluated, including the water-quality monitor, pump, seals, valve and pump settings, and the inspection ports.

Of the 24 SOD chamber deployments, only two did not result in data quality sufficient to calculate a linear regression. The two unsuccessful SOD chamber deployments can be attributed to equipment malfunction (seal failure inside of chamber) and failure of the circulator on the DO sensor to activate during chamber deployment (operator error). Of the eight control chamber deployments only one did not result in data quality sufficient to calculate a linear regression. This deployment was discounted because the plug in the bottom of the chamber (fig. 4B) was not intact during deployment. SOD values measured at this site were corrected with results from the control chamber deployed within 4 hours and in the same general location.

Internal Sediment Oxygen Demand Chamber Velocity

Regulating the circulation velocity is important when obtaining *in situ* SOD measurements. It is necessary for the velocity in the chamber to approximate velocity conditions at the sediment-water interface if the measurement is to be representative. If the circulation velocity within the chamber is significantly lower than that at or near the sediment-water interface, the molecular diffusion may be insufficient to replicate actual oxygen-consumption rates in a benthic environment (Hickey, 1986). Velocities in SOD chambers that are higher than those in the river at or near the sediment-water interface can resuspend bottom sediments. Resuspension is undesirable because it increases the turbidity of water inside the chamber and presumably increases the biological oxygen demand of the overlying water, thereby invalidating the SOD measurement (Wood, 2001). Sediment resuspension has been shown to increase the measured SOD value, and in some cases, shift chemical reaction kinetics from first order to zero order DO uptake (Buetel, 2003). Previous studies by the USGS in the Tualatin River Basin and Upper Klamath Lake have also shown that sediment resuspension during an SOD measurement can positively bias results (Wood, 2001; Doyle and Rounds, 2003). In order to document the effects of sediment resuspension, turbidity was monitored inside and outside each chamber. Efforts were made to obtain turbidity measurements from the river at all times during each deployment; however, due to equipment malfunction this was not always possible. Internal chamber turbidity measurements were successfully monitored throughout each deployment.

Average chamber turbidity and average ambient river turbidities were compared during each chamber deployment. These comparisons were designed to monitor any sediment resuspension inside the chambers that could result in anomalous SOD rates. Slightly higher turbidities were observed in some of the SOD chambers, particularly at RM 252.3, and for one deployment at RM 249.4, when values are compared to ambient river turbidities (table 1). In one chamber deployed at RM 249.4, an SOD rate of 2.6 g $O_2/m^2/day$ was measured with corresponding average chamber and river turbidities of 9.6 (NTU) and 9.5 (NTU), respectively. In another deployment at this site, the average chamber turbidity (18.3 NTU) was almost double the turbidity of that in the river (9.5 NTU) and the SOD rate was about 20 percent less (2.0 g $O_2/m^2/day$). At site RM 249.4, there does not appear to be any association between measured SOD rates and higher turbidities in the chambers (table 1).

Overall, SOD measurements obtained with average higher chamber turbidities generally fell within the range of SOD measurements with similar ambient/chamber turbidities (0.3 to 2.9 g $O_2/m^2/day$); however, for site 1 (RM 252.3, Lake Ewauna) the data in table 1 suggest a small possible association between higher chamber turbidities and higher SOD rate, but the association was not conclusive and therefore these SOD values were not discounted from the data set.

Quality Assurance of Sediment Sample Analysis

Approximately 20 percent of the 24 bottom sediment samples collected near each chamber deployment site were replicate analyses (a total of 29 samples). Replicate sediment samples analyzed for percent organic content were generally within 6 percent except for one sample that differed by 15 percent. Replicate sediment samples analyzed for percent finer than 63 microns were generally within 5 percent except for one sample that was within 30 percent. Both of the these outlier replicate values were from samples collected at RM 239.3, which is downstream of the Klamath Strait. The bottom sediment characteristics in this stretch of the Klamath River are the most variable among the sites (table 1), which might explain the higher degree of variability of replicates taken from this site. Overall, the results of these replicate analyses show good reproducibility by the analyzing laboratory.

Table 1. Sediment oxygen demand chamber deployment-site characteristics, conditions in chambers and river during deployment, sediment oxygen demand rates, sediment oxygen demand corrected to 20 degrees Celsius, and characteristics of bottom sediment near chambers. Groupings at each site indicate simultaneous, triplicate deployments.

[g O_2/m^2/day, grams of oxygen per square meter per day; NTU, nephelometric turbidity units; SOD, sediment oxygen demand; DO, dissolved oxygen; SOD_{20}, sediment oxygen demand at 20 degrees Celsius]

Site number	River mile	Date	Depth (meters)	Approximate percentage distance from left bank	SOD rate (g O_2/m^2/day)	SOD_{20} (g O_2/m^2/day at 20 degrees Celsius)	Average temperature during chamber deployment (Celsius)	Average turbidity in chamber (NTU)	Average turbidity in river (NTU)	Percentage of organic material in bottom sediment	Percentage of sediment finer than 63 microns
1	252.3	6/4/2003	1.6	70	2.9	2.9	19.9	33.0	8.3	17.6	76.7
1	252.3	6/4/2003	2.0	75	1.5	1.5	19.9	4.6	8.3	17.1	86.9
1	252.3	6/4/2003	2.7	60	0.8	0.8	19.8	7.5	8.3	19.8	83.9
1	252.3	6/4/2003	1.5	50	2.8	2.8	20.3	35.0	6.4	17.5	90.2
1	252.3	6/4/2003	1.5	50	1.2	1.1	20.3	5.4	6.4	17.4	90.3
1	252.3	6/4/2003	2.0	40	0.3	0.3	20.3	5.4	6.4	18.0	89.0
2	249.4	6/3/2003	2.4	70	2.5	2.6	19.6	9.6	9.5	19.7	94.3
2	249.4	6/3/2003	2.0	70	1.9	2.0	19.6	18.3	9.5	16.8	95.7
2	249.4	6/3/2003	2.7	60	2.2	2.2	19.6	11.0	9.5	18.9	93.2
2	249.4	6/3/2003	3.0	30	2.5	2.5	20.0	19.3	9.2	17.5	92.6
2	249.4	6/3/2003	2.3	30	1.5	1.5	20.0	18.3	9.2	18.0	81.8
2	249.4	6/3/2003	3.0	40	1.7	1.7	20.0		9.2	14.3	66.4
2	249.4	6/6/2003	2.7	40	3.0	2.9	20.6	27.7	--	17.7	95.1
2	249.4	6/6/2003	2.1	40	3.0	2.9	20.6	12.0	--	16.5	92.1
2	249.4	6/6/2003	3.0	50	1.9	1.9	20.4	6.0	--	17.6	92.7
3	244.2	6/2/2003	3.4	70	1.6	1.6	19.7	16.5	--	12.1	60.9
3	244.2	6/2/2003	3.5	70	0.6	0.6	19.7	8.3	--	7.7	67.7
3	244.2	6/2/2003	DO sensor not functioning properly during chamber deployment. No SOD measurement was obtained from this deployment								
4	239.3	6/5/2003	3.0	40	2.1	2.0	21.0	16.5	5.8	4.8	12.0
4	239.3	6/5/2003	3.3	40	2.1	2.0	20.8	8.0	5.8	15.2	96.1
4	239.3	6/5/2003	3.3	20	0.5	0.4	21.0	4.8	5.8	12.9	85.0
4	239.3	6/5/2003	2.7	40	1.4	1.3	21.0	20.3	12.4	15.6	55.6
4	239.3	6/5/2003	Silicon seal inside of chamber failed and river water leaked into chamber. No SOD measurement was obtained from this deployment								
4	239.3	6/5/2003	1.9	75	0.6	0.5	21.0	5.2	12.4	13.3	7.8

Results and Discussion

Sediment Oxygen Demand Rates and Spatial Variability

Six SOD measurements were obtained at the Lake Ewauna site (RM 252.3). The distribution of SOD_{20} ranged from 0.3 to 2.9 g O_2/m^2/day. The median SOD_{20} value measured at this location in the river was 1.3 g O_2/m^2/day. Linear regression coupled with a Pearson r test show that SOD rates measured at this site were not significantly correlated with chamber location in the cross-section or depth of chamber deployment (fig. 6). (Location in the stream cross-section and depth affect current velocity, which can in turn affect the sediment characteristics of the streambed.) The area downstream of the Klamath Falls sewage treatment plant on the left bank of Lake Ewauna was avoided as a chamber deployment location to protect the health of divers and because sediments adjacent to the outfall may not be representative of overall conditions in this water body.

Nine successful SOD chamber deployments were made at RM 249.4. Measured SOD_{20} values ranged from about 1.5 to 2.9 g O_2/m^2/day, with a median value of 2.2 g O_2/m^2/day. In general, chamber location in the cross-section and depth of deployment were not significantly correlated with measured SOD_{20} rate (fig. 7).

The mean SOD_{20} value measured at RM 244.2 was 1.1 g O_2/m^2/day, based on two successful deployments. RM 244.2 was not one of the locations originally sampled in 1994 by ODEQ; however, it was selected for this study to improve spatial coverage of the SOD measurements. There was about a 10 river-mile gap between the study sites from RM 249.4 to RM 239.3. The RM 244.2 site is approximately midway between the lower two deployment sites and was a suitable location to standardize chamber deployment procedures on the first day of data collection (fig. 3).

SOD_{20} values measured at RM 239.3 ranged from 0.4 to 2.0 g O_2/m^2/day, with a median value of 1.3 g O_2/m^2/day, based on five successful deployments (table 1). There was no significant correlation between chamber location in the cross-section and the measured SOD_{20} rate (fig. 8A), but chamber deployment depth and SOD_{20} rate showed a slight positive relationship (fig. 8B).

Overall, the variability of individual SOD measurements at a site was equal to or greater than the variability among sites. Consequently, rather than concluding that SOD rates differ significantly among sites, it would be more reasonable to use the median SOD_{20} rate for the entire study reach (1.8 g O_2/m^2/day) in water-quality models and other analyses.

Water-Column Oxygen Demand Measured in Control Chambers

Oxygen depletion rates measured in the control chambers (corrected to 20 degrees Celsius using equation [2]), ranged from 1.11 to 1.80 mg O_2/L/day, and had a median value (n=7) of 1.44 mg O_2/L/day (table 2). Although the oxygen depletion rate in a control chamber is not equivalent to a standard biological oxygen demand (BOD) measurement, it does provide information as to the potential oxygen demand in the water column without photosynthesis. It also provides insights as to the relative importance of oxygen demand in the water column versus the bottom sediments, at least for early June, 2003.

An areal rate for the water-column oxygen demand can be obtained for each site by multiplying the temperature corrected oxygen depletion rate in a control chamber by the average depth (in meters) at a deployment site (table 2). These temperature-corrected rates ranged from 3.0 to 4.7 g O_2/m^2/day, and had a median rate of 3.8 g O_2/m^2/day (table 2), which is roughly double the median SOD_{20} rate (1.8 g O_2/m^2/day) given in table 1. This result is not unexpected. Massive summer algal blooms develop each year in Upper Klamath Lake, and its labile organic matter is transported downstream into

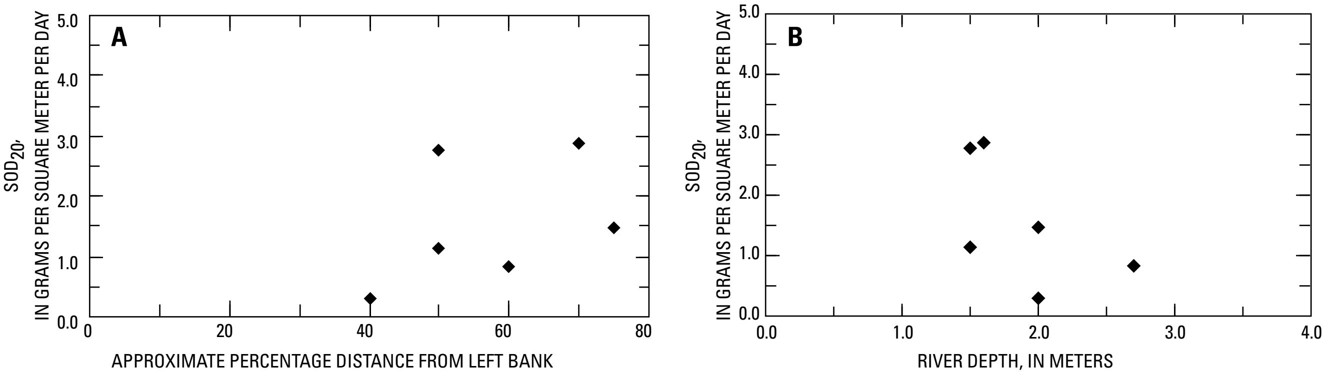

Figure 6. Sediment oxygen demand at 20 degrees Celsius as a function of (A) chamber location in the cross-section and (B) depth of chamber deployment, at RM 252.3 (Lake Ewauna).

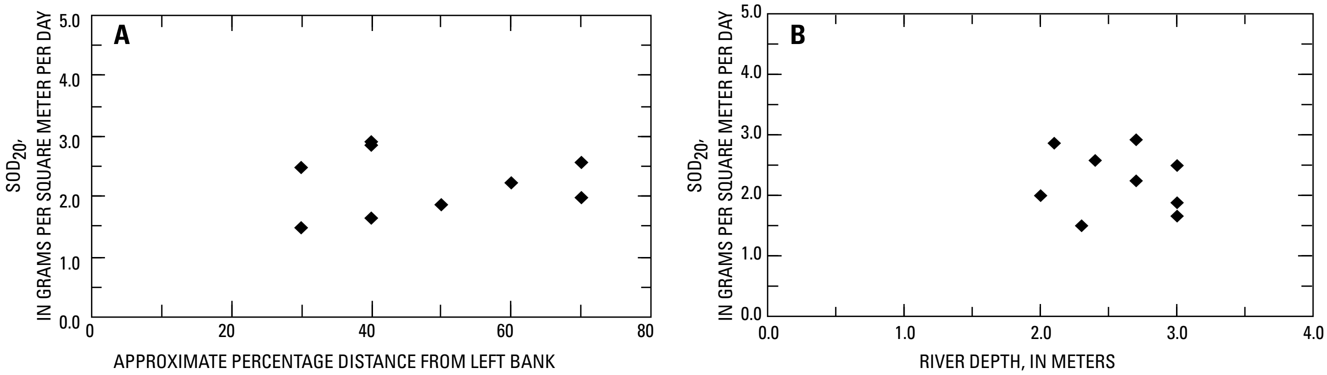

Figure 7. Sediment oxygen demand at 20 degrees Celsius as a function of (A) chamber location in the cross-section and (B) depth of chamber deployment, at RM 249.4.

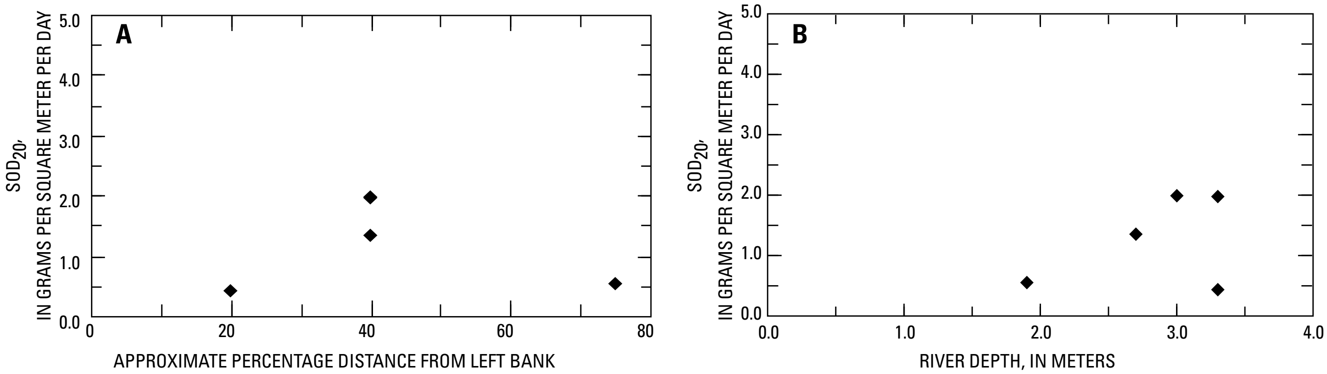

Figure 8. Sediment oxygen demand at 20 degrees Celsius as a function of (A) chamber location in the cross-section and (B) depth of chamber deployment, at RM 239.3.

Table 2. Water-column oxygen demand rates estimated from control chambers.

[m, meter; mg/L/day, milligrams per liter per day; g O_2/m^2/day, grams of oxygen per square meter per day]

River mile	Date	Average temperature (degrees Celsius)	Average depth (m)	Oxgen depletion rate (mg/L/day)	Oxygen depletion rate corrected to 20 degrees Celsius (mg/L/day)	Water-column Oxygen demand corrected to 20 degrees Celsius (g O_2/m^2/day)
239.3	6/5/2003	21.0	3.2	1.45	1.36	4.4
239.3	6/5/2003	21.1	2.3	1.85	1.73	4.0
244.0	6/2/2003	19.6	3.4	1.08	1.11	3.8
249.4	6/3/2003	19.7	2.4	1.48	1.51	3.6
249.4	6/3/2003	20.0	2.8	1.24	1.24	3.5
249.4	6/6/2003	20.7	2.6	1.88	1.80	4.7
252.3	6/4/2003	19.9	2.1	1.43	1.44	3.0

Lake Ewauna and the Klamath River, where it can decompose and cause severe hypoxia. Others researching the severe loss of DO in the Keno reach of the Klamath River have reached a similar conclusion (Eilers and Raymond, 2003). It is important to note that the amount of organic matter transported from Upper Klamath Lake in early June 2003 (this study) may have been smaller than what is normally delivered when algal blooms peak in the lake, typically from late June through September (Wood and others, 1996). Therefore, it is not unexpected that the lowest DO values observed in the Klamath River, typically beginning in July and extending into October (fig. 1), closely correspond to the timing of lake algal blooms.

It is not clear whether the organic matter transported out of Upper Klamath Lake is decomposing primarily in the water column, as suggested by the results from the oxygen depletion rates in the control chambers, or whether much of this labile organic matter settles to the river bottom and temporarily elevates SOD rates. SOD measured in Upper Klamath Lake show that rates can become temporarily elevated, presumably due to the recent deposition of organic matter following the crash of an algal bloom (Wood, 2001). The SOD_{20} rate in Ball Bay, a northern embayment of upper Klamath Lake, rose from 1.5 g O_2/m^2/day in May 1999 to >9.6 g O_2/m^2/day in August 1999, a sevenfold increase. Similarly, decomposing algal blooms in Howard Bay, a southwestern embayment of Upper Klamath Lake, produced DO concentrations too low to even attempt an SOD measurement in August 1999.

The combined areal oxygen demand (SOD_{20} plus water-column oxygen demand corrected to 20 degrees Celsius) had a median value of 5.6 g O_2/m^2/day in early June 2003. Assuming an average water depth of 2.7 meters and a water temperature of 20 degrees Celsius in early June (table 2), water leaving Upper Klamath Lake could lose about 2.1 mg/L of oxygen per day, assuming no intervening photosynthesis or reaeration. Consequently, in a period of about 2.7 days, which is approximately the time-of-travel to the water-quality monitor located 10.8 kilometers downstream of Upper Klamath Lake (fig. 1), the total water-column DO loss could reach 5.6 mg/L in June 2003. For July 2003, when water temperatures rose to 23 degrees Celsius (fig. 1) and time-of-travel to the water-quality monitor increased to about 3.8 days, the total water-column DO loss could reach 9.6 mg/L, which could more than explain the extremely low DO values measured at the water-quality monitor in July 2003 (fig. 1). Time-of-travel to the water-quality monitor was estimated using (1) mean-monthly streamflows for June and July 2003 (25. 3 and 17.6 cubic meters per second, respectively) at the Klamath River at Keno streamgage (Herrett and others, 2004), (2) a travel distance of 10.8 kilometers, (3) an average depth of 2.7 meters, and (4) an average channel width of 200 meters.

These estimates of DO loss from water traveling from Upper Klamath Lake to a location 10.8 kilometers downstream assume that reaeration and photosynthesis rates were negligible, which may not be the case. Therefore, these values represent worse-case DO losses. However, the estimated DO loss for July 2003 is based on SOD and water-column demand rates measured in June 2003. As discussed previously, the July values could be significantly underestimated if larger amounts of labile organic matter left Upper Klamath Lake in July than in June 2003. Regardless of the exact rates of the terms in a DO budget (e.g. SOD, water-column oxygen demand or BOD, photosynthesis, and reaeration), it is clear that SOD and water-column oxygen demand are important terms in this system and may largely explain the hypoxia that develops each summer in Lake Ewauna and the Klamath River above Keno.

Bottom-Sediment Characteristics

Bottom sediments generally had similar physical characteristics among the locations selected for SOD measurements in the study area. There were some differences, however, that are worth noting. The upper section, from Lake Ewauna to above the Klamath Strait (fig. 3), tended to have a greater amount of buried bark chips and other woody debris. Most of the wood chips appeared to be bark from ponderosa pines, which have been the favored trees for timber harvest in the basin (Risley and Laenen, 1999). Harvested logs have been transported and stored in the upper reaches of the Klamath River in order to supply sawmills near Klamath Falls, Oregon. This activity has declined over the past few decades along with the number of sawmills. At many locations bark is buried under 10 cm (centimeters) or more of bottom sediments, indicating that old bark is being buried under fresh sediment. Bark chips retrieved by divers, some of it buried under 50 cm or more of bottom material, showed little sign of decomposition in these highly reducing sediments. The bark was brittle and discolored, but overall it looked similar to freshly deposited material. The lack of apparent decomposition suggests that the buried woody debris contains primarily refractory organic matter and likely contributes little to the SOD in the river.

Farther down the reach, in the vicinity of RM 239.3, there were similar sediment deposits, but they appeared to contain smaller bark chips, woody debris, a higher concentration of sand-sized particles, and an overall lower percentage of organic material (table 1 and fig. 9). At some deployment locations there was 10-15 cm of sediment atop sandier material that may have been characteristic of the bottom prior to, or soon after, channel modifications associated with the construction of Keno Dam. The downstream location for SOD measurements (RM 239.3) was downstream of Klamath Strait drain, which is the primary drain from the Bureau of Reclamation's Klamath Irrigation Project. This drain may be a source of organic matter and sediment from the project, but SOD rates measured below this drain were not significantly different than the three upstream study locations (table 1).

Correlations between SOD_{20} and percentage of organic material, and SOD_{20} and percentage of sediment finer than 63 microns were assessed. Results showed that there was no correlation between SOD_{20} rates and percent organic material measured in bottom sediments at any of the selected sites.

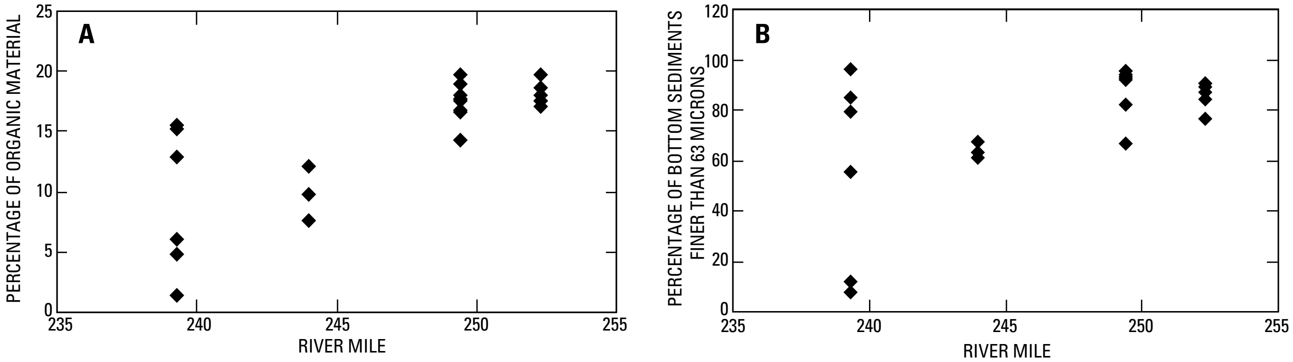

Figure 9. Percentage of (A) organic material measured in bottom sediments and (B) bottom sediments finer than 63 microns.

There was a slight linear correlation between the percentage of bottom sediments finer than 63 microns and SOD_{20} rate at RM 249.4, but not at the other sites. The two highest SOD_{20} rates measured at this site (both 2.9 g O_2/m^2/day) had corresponding percentages of sediment finer than 63 microns of 95.1% and 92.1% (table 1). In contrast, the sample with the highest percentage of sediment finer than 63 microns (95.7%) collected at this site had a corresponding SOD_{20} rate of about 2.0 g O_2/m^2/day, about 30% lower than the rate measured in samples of similar sediment. There was also an SOD_{20} measurement of 1.9 g O_2/m^2/day with a corresponding percentage of sediment finer than 63 microns sample of 92.7%, which is a similar percentage as for the two highest SOD_{20} measurements at this site. The lowest SOD_{20} values measured at river mile 249.4 of 1.5 and 1.7 g O_2/m^2/day had corresponding percentages of sediment finer than 63 microns samples of 81.8% and 66.4% respectively (table 1), which were the lowest from this site. These values suggest that there is not a clear association between the two variables, but also that enough of a potential relationship exists that it cannot be dismissed.

Based on this assessment of the potential correlations between sediment characteristics and SOD_{20} rate, it does not appear that SOD can be readily determined from either of the two sediment characteristics selected for this study. Future attempts to correlate SOD with sediment characteristics might 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 sediment is metabolized (Wood, 2001). In addition, correlating SOD with characteristics of the top few centimeters of sediment, rather than the top 15–20 centimeters attempted in this study, might yield better results. Most oxygen demand exerted by sediments probably occurs in the top few centimeters because it is fresher material (more recently deposited) and because of its proximity to the oxygen source.

Comparison of Sediment Oxygen Demand Rates in Lake Ewauna and the Klamath River to Those in Upper Klamath Lake

SOD_{20} rates measured during this study were compared to SOD_{20} rates measured in Upper Klamath Lake in 1999 (Wood, 2001). This comparison was prompted by a review of SOD measurements (CH2M HILL and Wells, 1995) obtained from another study of the Klamath River done by Oregon Department of Environmental Quality, in which SOD rates were estimated to be an order of magnitude higher than rates measured in Upper Klamath Lake. There was speculation that woody debris associated with the transport and storage of logs on the Klamath River may be an important source of organic matter causing these high SOD rates (Mayer, 2001).

The median SOD_{20} rates measured in Upper Klamath Lake during the spring and summer of 1999 were 1.6 and 1.7 g O_2/m^2/day, respectively (Wood, 2001), compared to a median SOD_{20} rate of 1.8 g O_2/m^2/day in Lake Ewauna and the Klamath River during this study. The interquartile range of Upper Klamath Lake SOD_{20} values were 1.4 to 2.2 and 1.6 to 2.2 g O_2/m^2/day for the spring and summer of 1999, respectively, compared to 1.1 to 2.5 g O_2/m^2/day in the Klamath River measured in June 2003. The larger interquartile range in the Klamath River is not unexpected because riverine depositional environments are typically more spatially heterogeneous than lake environments.

A Tukey's multiple comparison test (Helsel and Hirsh, 1992) comparing the SOD_{20} rates measured in the Klamath River during this study to the rates measured in the spring and summer of 1999 in Upper Klamath Lake showed no significant difference between the median SOD_{20} rates. The fact that SOD rates in Upper Klamath Lake, which does not contain bark or woody debris, are similar to rates in the Klamath River, suggests that the woody debris in the Klamath River is not the primary contributor to SOD. More likely, algal production in Upper Klamath Lake and the subsequent transport of this organic matter to Lake Ewauna and the Klamath River above Keno Dam is a more important source of labile organic matter to bottom sediments in all three water bodies. This conclusion is also supported by the summer DO concentrations recorded 10.8 kilometers downstream of Upper Klamath Lake (fig. 1). DO values in this river reach should be relatively stable and low if it were primarily controlled by SOD associated with a nearly unlimited supply of buried woody debris. However, the fact that DO periodically rebounded to over 4 mg/L during the summer, such as in middle August and the last half of September, 2003 (fig. 1), suggests that DO is significantly influenced by a more variable source of organic matter, such as the delivery of labile organic matter from algal blooms in Upper Klamath Lake. The variability in the concentration of organic matter leaving Upper Klamath Lake can result from variations in algal bloom density and, perhaps more importantly, from variations in wind direction that either push surface "scums" of algae toward or away from the lake's outlet, which is located at the southern end of the lake (fig. 3). Visual observations over the years have demonstrated that algal bloom densities can increase markedly in bays, nearshore areas, and/or the extremities of Upper Klamath Lake, depending on wind speed and direction.

Summary and Conclusions

Sediment oxygen demand (SOD) is the rate at which dissolved oxygen is removed from the water column during the decomposition of organic matter in streambed or lakebed sediments. In lakes and slow moving rivers, or rivers with high levels of organic matter in the bed sediment, SOD can be a major cause of low dissolved oxygen (DO) concentrations in the water column. Low DO concentrations can be detrimental to fish and other aquatic life in a stream or lake.

Extreme hypoxia that develops every year in the Klamath River below Upper Klamath Lake is a threat to the survival of two endangered sucker species. In an effort to better understand the oxygen dynamics in this river reach, and to aid in parameterizing water-quality models, measurements of SOD were made. In June 2003, replicate SOD measurements were made at one site in Lake Ewauna and three sites in the Klamath River above Keno Dam. Individual measurements of SOD_{20} rates (temperature corrected to 20 degrees Celsius) ranged from 0.3 to 2.9 g O_2/m^2/day (grams of oxygen per square meter per day), with a median value of 1.8 g O_2/m^2/day (n=22). The variability of individual SOD measurements at a site was equal to or greater than the variability of SOD rates among the four sites. Consequently, the overall median SOD for the entire study reach should be used when parameterizing water-quality models.

SOD values measured in this study are about 10 times smaller than estimates made in this study area by the Oregon Department of Environmental Quality (ODEQ) in 1994. However, ODEQ considered their measurements to be rough estimates at best because of difficulties associated with measuring SOD of soft sediments. Provisions were made in this study to avoid similar problems by modifying the SOD chambers. The rates measured in the Klamath River are similar to SOD_{20} rates measured several miles upstream in Upper Klamath Lake in the spring and summer of 1999, which had medians of 1.6 and 1.7 g O_2/m^2/day, respectively. These findings indicate that the unusually high SOD rates in the Klamath River probably result from causes other than the presence of large amounts of woody debris in bottom sediments from past and ongoing sawmill operations, which has been suggested by other investigators.

An areal rate of water-column oxygen demand was estimated from control chambers during the study. In early June 2003, the median rate was 3.8 g O_2/m^2/day, which was more than double the SOD_{20} rate. Taken together, the SOD and water-column oxygen demand can more than account for the severe hypoxia that develops in this reach of the Klamath River from July into October of most years. The largest source of labile organic matter contributing to this hypoxia likely comes from algal blooms in Upper Klamath Lake. This conclusion is also supported by the summer DO concentrations recorded 10.8 kilometers downstream of Upper Klamath Lake in 2003. DO values in this river reach should be relatively stable and low if it were primarily controlled by SOD associated with a nearly unlimited supply of buried woody debris. However, the fact that DO periodically rebounded to over 4 mg/L during the summer suggests that DO is significantly influenced by a more variable source of organic matter, such as the delivery of labile organic matter from algal blooms in Upper Klamath Lake. The variability in the concentration of organic matter leaving Upper Klamath Lake can result from variations in algal bloom density and, perhaps more importantly, from variations in wind direction that either push surface "scums" of algae toward or away from the lake's outlet.

Bottom sediments had similar physical characteristics among the locations selected for SOD measurements. The upper section, however, generally from Lake Ewauna to above the Klamath Strait, tended to have a greater amount of buried bark chips and other woody debris originating from logs transported and stored on the Klamath River, whereas sites below the Klamath Strait tended to have more sand-sized particles. Correlations between SOD_{20} and percentage of organic material, and SOD_{20} and percentage of sediment finer than 63 microns, were calculated. Based on these correlations, SOD could not be reliably determined from either of the two sediment characteristics. Bark retrieved by divers, some of it buried under 50 cm or more of bottom material, showed little sign of decomposition in these highly reducing sediments. The bark was brittle and discolored, but otherwise it looked very similar to freshly deposited material. The lack of apparent decomposition further suggests that the buried woody debris contains primarily refractory organic matter and likely contributes little to the SOD in the river.

References Cited

Beutel, M., 2003, Hypolimnetic anoxia and sediment oxygen demand in California drinking water reservoirs: Lake and Reservoir Management v. 19, no. 3: 208–221.

Caldwell, J.M., and Doyle, M.C., 1995, Sediment oxygen demand in the lower Willamette River, Oregon, 1995: U.S. Geological Survey Water-Resources Investigations Report 95–4196, 14 p.

CH2M Hill, and Wells, S., 1995, Water quality model of the Klamath River between Link River and Keno Dam: Draft report for the Oregon Department of Environmental Quality, [variously paged].

Doyle, M.C. and Rounds, S.A., 2003, The effect of chamber mixing velocity on bias in measurement of sediment oxygen demand rates in the Tualatin River, Oregon: U.S. Geological Survey Water-Resources Investigations Report 03–4097, 16 p.

Eilers J.M., and Raymond R., 2003, Sediment oxygen demand and nutrient release from sites in the Klamath Hydropower Project: Bend, Oregon, J.C. Headwaters, Inc., 63 p.

Fishman M.J., and Friedman, L.C., eds., 1989, Methods for determination of inorganic substances in water and fluvial sediments (3d ed.): U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. 1, 545 p.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. 1, 58 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier Publishers, 522 p.

Herrett, T.A., Hess, G.W., House, J.G., Ruppert, G.P., and Courts, M.L., 2004, Water resources data, Oregon, water year 2003: U.S. Geological Survey Water-Data Report, OR–03–01, 529 p.

Hickey C.W., 1986, Chamber studies of benthic oxygen uptake kinetics in the Waiotapu River, New Zealand, *in* Hatcher, K.J., ed., Sediment oxygen demand—Processes, modeling, and measurement: Athens, University of Georgia, Institute of Natural Resources, p. 37–61.

Kelly V.J., 1997, Dissolved oxygen in the Tualatin River, Oregon, during winter flow conditions, 1991 and 1992: U.S. Geological Survey Water-Supply Paper 2464–A, 68 p.

Mayer, T., 2001, Water quality impacts of the Klamath Straits Drain on the Klamath River, *in* Trehey, G.H., comp., Proceedings of the 2001 Klamath Basin Fish & Water Management Symposium, Arcata, California, May 22–25, 2001: Klamath River Inter-Tribal Fish and Water Commission and Humboldt State University, 40 p.

Murphy, P.J., and Hicks, D.B., 1986, In-situ method for measuring sediment oxygen demand, *in* Hatcher, K.J., ed., Sediment oxygen demand—Processes, modeling, and measurement: Athens, Georgia, Institute of Natural Resources, University of Georgia, p. 307–322.

Porcella, D.B., Mills, W.B., and Bowie, G.L., 1986, A review of modeling formulations for sediment oxygen demand, *in* Hatcher, K.J., ed., Sediment oxygen demand—Processes, modeling, and measurement: Athens, University of Georgia, Institute of Natural Resources, p. 121–138.

Risley, J.C., and Laenen, A., 1999, Upper Klamath Lake Basin nutrient-loading study-assessment of historic flows in the Williamson and Sprague Rivers: U.S. Geological Survey Water-Resources Investigations Report 98–4198, 22 p.

Rounds, S.A. and Doyle, M.C., 1997, Sediment oxygen demand in the Tualatin River Basin, Oregon, 1992-96: U.S. Geological Survey Water-Resources Investigations Report 97–4103, 19 p.

Rounds, S.A., Wood, T.M., and Lynch, D.D., 1999, Modeling discharge, temperature, and water quality in the Tualatin River, Oregon: U.S. Geological Survey Water-Supply Paper 2465–B, 121 p.

Thomann, R. V., and Mueller, J.A., 1987, Principles of surface water quality modeling and control: New York, Harper and Row, p. 291–293.

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.

Wood, T.M., Fuhrer, G.J., and Morace, J.L., 1996, Relation between selected water-quality variables and lake level in Upper Klamath and Agency Lakes, Oregon: U.S. Geological Survey Water-Resources Investigations Report 96–4079, 57 p.

Back cover:
Downstream view of Klamath River showing log storage in river near river mile 251.
Photograph by Dennis D. Lynch (U.S. Geological Survey).

Doyle and Lynch—**Sediment Oxygen Demand in Lake Ewauna and the Klamath River, Oregon, June 2003**—SIR 2005–5228

Printed on recycled paper