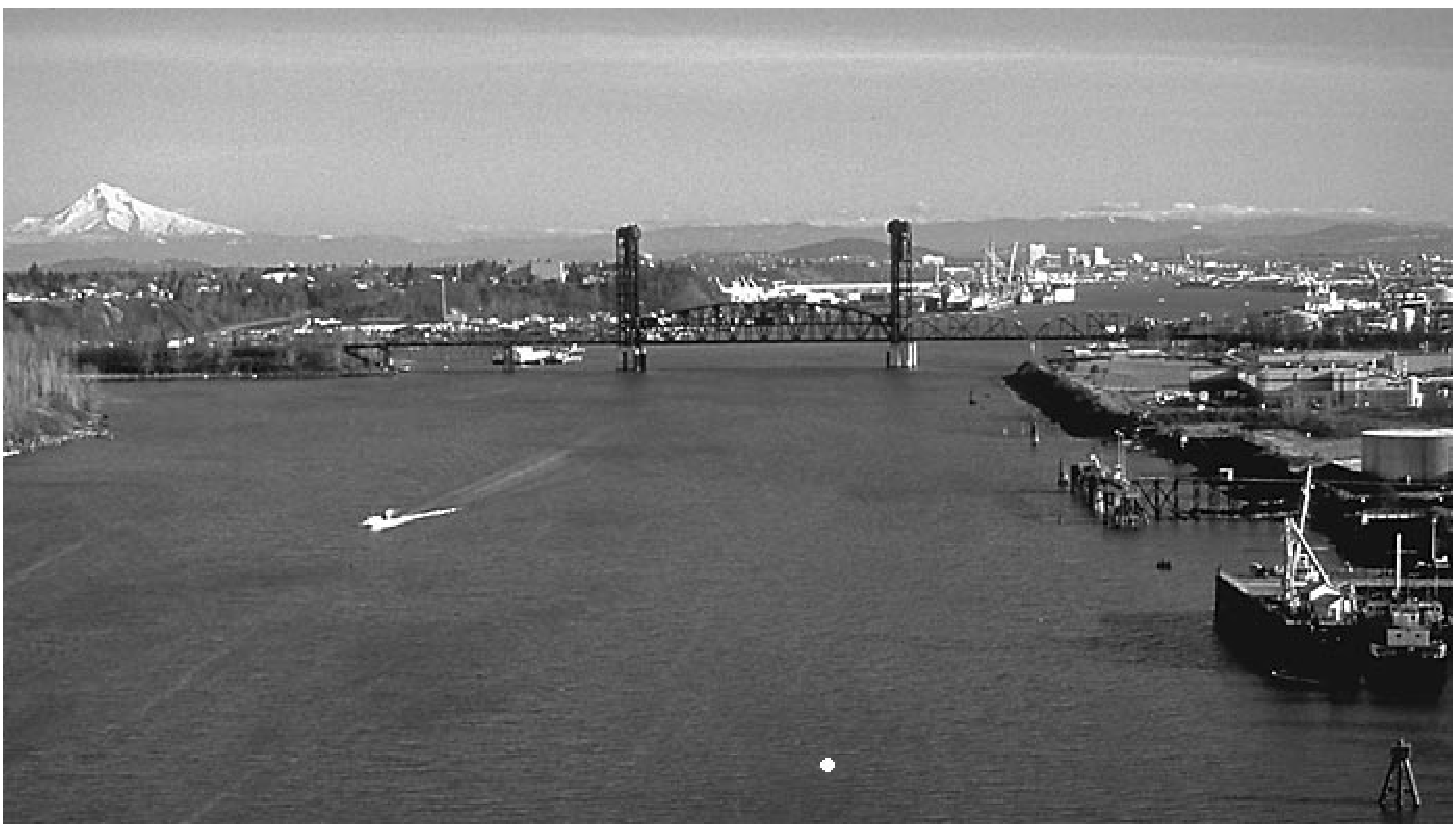
Sediment Oxygen Demand in the Lower Willamette River, Oregon, 1994

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95–4196

Prepared in cooperation with
OREGON DEPARTMENT OF ENVIRONMENTAL QUALITY



Cover photograph. Looking upstream at the Willamette River with Mt. Hood and Portland Harbor in the background, February 7, 1993. *(Photograph by Dennis A. Wentz, U.S. Geological Survey.)*

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By James M. Caldwell and Micelis C. Doyle

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Portland, Oregon
1995

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FACTORS

Multiply	By	To obtain
acre	4,047	square meter (m^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter (m^3/s)
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter (m^3/s)

Temperature in degrees Celsius (°C) as follows:

$$°C = (°F-32)/1.8.$$

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Abstract

An investigation of sediment oxygen demand (SOD) at the interface of the stream and stream bed was performed in the lower Willamette River (river mile 51 to river mile 3) during August, 1994, as part of a cooperative project with the Oregon Department of Environmental Quality. The primary goals of the investigation were to measure the spatial variability of SOD in the lower Willamette River and to relate SOD to bottom-sediment characteristics.

The SOD chambers used in the study were open-bottomed, opaque plastic cylinders that were seated and sealed on the river bottom by scuba divers. When seated, the chambers contained 52 liters of isolated river water, which was slowly recirculated for at least 2 hours over 0.225 square meters of relatively undisturbed bottom sediment. These chambers could not be deployed in areas with gravels and cobbles, which represent about 55 percent of the study area above Willamette Falls and 30 percent of the river below Willamette Falls.

Sediment oxygen demand is commonly reported as grams of oxygen consumed per square meter of bottom sediment per day ($g/m^2 \cdot day$). The measured SOD rates, corrected to a temperature of 20 degrees C, ranged from 1.3 to 4.1 $g/m^2 \cdot day$ in the lower Willamette River. The SOD measured above and below Willamette Falls averaged 2.0 and 2.1 $g/m^2 \cdot day$, respectively. After adjusting for the amount of bottom material composed of gravels and cobbles, the best estimates for reachwide SOD rates above and below Willamette Falls are 1.4 (± 0.5) and 1.8 (± 0.3) $g/m^2 \cdot day$, respectively

Sediment samples were collected near each chamber and analyzed for percent water, percent sand, and percent organics. The sand content ranged from 0.1 to 6.2 percent and averaged 1.8 percent. The organic content ranged from 1.4 to 9.6 and averaged 5.6 percent. No statistically significant correlations were found between these sediment characteristics and sediment oxygen demand.

INTRODUCTION

Background

Dissolved oxygen (DO) has been an important index of water quality in the Willamette River since the first field measurements were made in 1926. Historically, during low-flow seasons, water in Portland Harbor (river mile [RM] 26.5 to the mouth) was often devoid of oxygen (Gleeson, 1972). With the introduction of basinwide secondary wastewater treatment, improved paper pulping processes, and summer flow augmentation, there was a marked improvement in DO concentrations.

The role of bottom sediments in the depletion of DO is known to be an important component in the overall oxygen budget. The depletion of oxygen from the water overlying the bottom sediment is primarily caused by the decomposition of organic matter in the sediments.

Direct measurements of sediment oxygen demand (SOD) in the Willamette River were first made in 1969 (Thomas, 1970). During July of that year a maximum SOD rate of 19.5 grams of oxygen consumed per square meter of bottom sediment per day ($g/m^2 \cdot day$) was observed near RM 21 at 16°C. Because point discharges of organic matter to the Willamette River were considerable at that time, much of the 1969 data does not adequately reflect current conditions. Studies of DO in Portland Harbor in 1976 and 1979 performed by the U.S. Geological Survey (USGS) suggested that one significant cause of DO consumption was total benthic oxygen demand (Hines and others, 1977; McKenzie and others, 1979). In a follow-up study, it was estimated that 15 to 30 percent of the DO consumption in Portland Harbor was due to SOD during summer low-flow periods (S.W. McKenzie, USGS, unpub. data, 1981).

During the summers of 1992–94, the USGS measured SOD in the Tualatin River, a major tributary to the Willamette River, and found SOD to be an important sink for DO (Kelly, in press; S.A. Rounds and others, USGS, unpub. data, 1995). Equipment and standardized procedures for the direct measurement of SOD were developed during that study. With this knowledge, experience and equipment, the USGS in cooperation with the Oregon Department of Environmental Quality (ODEQ), undertook this study of SOD in the lower Willamette River in order to provide information needed to construct and calibrate a DO model of the lower river.

Purpose and Scope

The purpose of this report is to present the results of SOD measurements and bottom-sediment analyses from 15 selected sites in the lower Willamette River (RM 51 to RM 3). This report describes the methods and procedures used in this study and documents how reported values were calculated. These data are important to the calibration and use of DO models of the Willamette River.

Study Area

This study focused on the lower 51 miles of the Willamette River (fig. 1). The Willamette River drains an 11,460 square mile area in northwestern Oregon. The basin is bounded on the south by the Calapooya Mountains, on the east and west by the Cascade and Coast Ranges, respectively, and on the north by the Columbia River. The Willamette River flows northward to its confluence with the Columbia in Portland. The alluvial deposits that border rivers in the valley consist of interbedded layers of clay, silt, sand, and gravel (Willamette Basin Task Force, 1969).

The study area comprises two distinct reaches, Newberg Pool and Portland Harbor. Newberg Pool extends from the city of Newberg (RM 51) to Willamette Falls (RM 26.5) at Oregon City. This depositional reach is deep and slow-moving. Midchannel depths range from 15 feet to 100 feet and average about 25 feet. Mean velocities ranged from 0.48 feet per second (ft/s) to 0.85 ft/s and averaged 0.57 ft/s during the study period. Newberg pool is analogous to a long lake behind a dam, with water level changes at the falls measurable as far upstream as Newberg. Removal of sand and gravel from Newberg Pool by private contractors using dredging equipment is authorized by permit. In 1993, approximately 840,000 cubic yards of bottom material was dredged between RM’s 32 and 50.3 (Joe Bernert Towing Co., Inc., written commun., 1994).

Portland Harbor extends from Willamette Falls to the mouth of the Willamette River. In this 26.5-mile reach, the river is deep, slow-moving, and tidally influenced. Midchannel depths range from 10 feet to 140 feet and average about 45 feet. During times of medium and low flows, tidal effects are evident at Willamette Falls; reverse flow has been measured as far upstream as Ross Island (RM 15) during low-flow periods. During the study period, the maximum velocities reached 0.5 ft/s during both rising and falling tides at RM 12.8. Portland Harbor has been dredged to provide a shipping channel typically 300 feet wide and 40

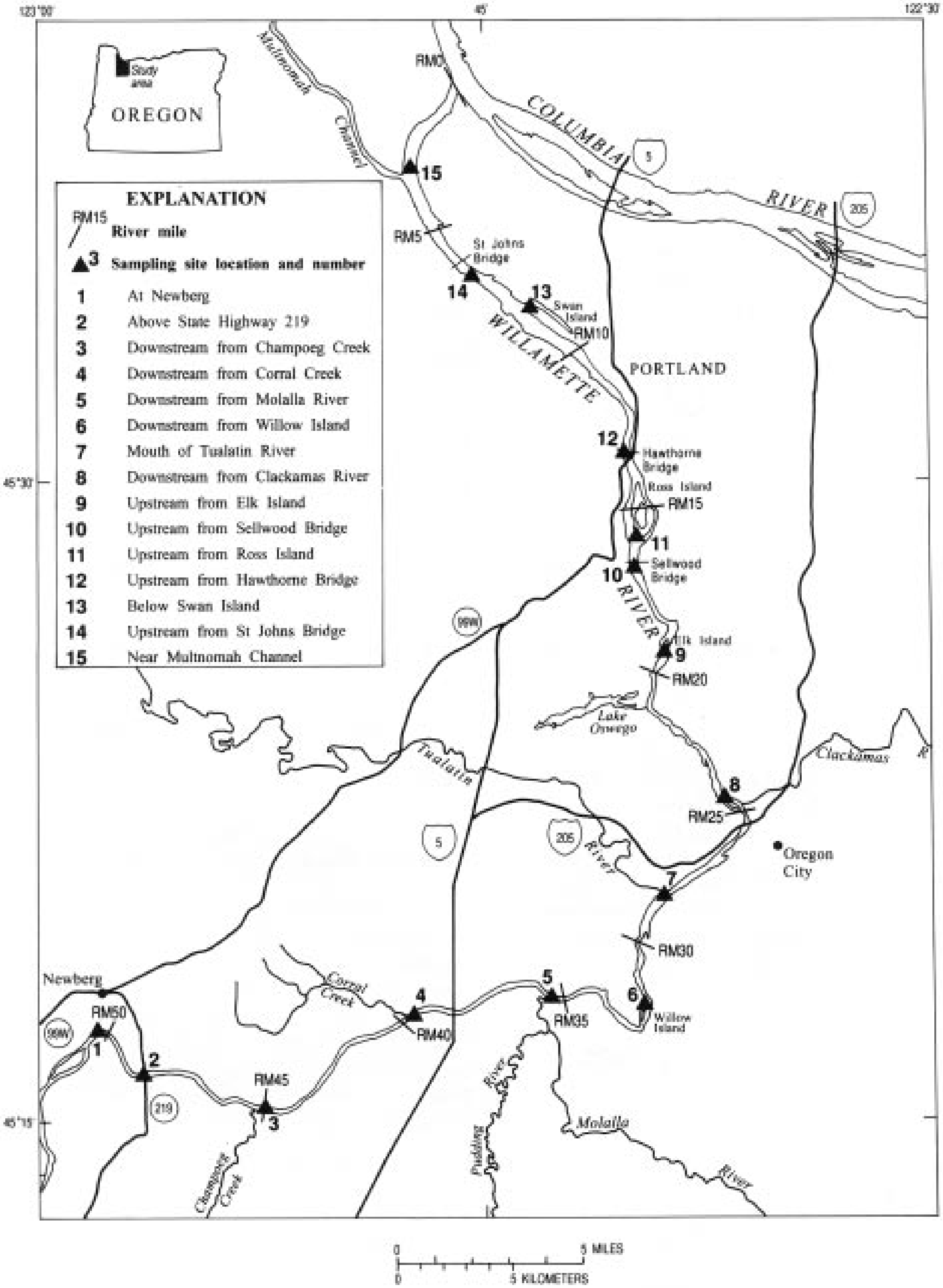

Figure 1. Location of sediment oxygen-demand sampling sites, Willamette River, Oregon.

feet deep from the mouth of the Willamette River upstream to the Broadway Bridge (RM 11.8). Between 1986 and 1990, about 800,000 cubic yards of bottom material were dredged from the channel (U.S. Army Corps of Engineers, 1992).

Water moves very slowly in Portland Harbor during low-flow conditions, and tidal effects commonly cause flow reversals and local eddy currents. A wedge of cooler Columbia River water periodically migrates upstream under the warmer Willamette River water. This phenomenon was observed near Multnomah Channel at RM 3 during the study. Columbia River water has been detected as far upstream in the Willamette River as RM 12.8.

Acknowledgments

The authors express their gratitude to the following people and organizations: Larry Caton of the ODEQ for information and assistance in the use and construction of the SOD chambers; Thomas Bernert of Joe Bernert Towing Company Inc., and Jim Britton and Mark Siipola of the U.S. Army Corps of Engineers for providing the channel dredging information; Tarang Khangaonkar of ENSR Consulting and Engineering for additional information on SOD; Thomas K. Edwards, Dennis D. Lynch, James E. Poole, Gregory W. Olsen, Kenneth A.Skach, and Daniel K. Zimmerman—the USGS divers and assistants on this project; and Allison Bennett and Michelle Van Hise for assisting with various aspects of this project as USGS volunteers.

METHODS AND PROCEDURES

Sampling Approach

Site selection for the SOD measurements was based on results from a field reconnaissance, as well as on information from bathymetric maps of the Willamette River, channel dredging maps, conversations with U.S. Army Corps of Engineers personnel, and measurements of DO concentrations in the water column. On the basis of this information, 15 stations were chosen that provided good geographical coverage of the study area (fig. 1).

Field reconnaissance of the study area included measuring DO concentrations, collecting and inspecting bottom-sediment samples, and determining the location of each station by using a global positioning system device. Measurements of DO were taken near the river surface and near the bottom of the water column using a Hydrolab H20 multiparameter water-quality instrument. Temperature, specific conductance, pH, and water-column depth were also measured. Samples of bottom sediment were obtained by using an Eckman dredge sampler. Each 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. The sampler was deployed a total of 118 times in the river reach during the reconnaissance. The Eckman dredge sampler did not retrieve a bottom sediment sample if large gravels, cobbles, or a hard bottom were encountered.

Sediment Oxygen-Demand Chambers

Three in-situ chambers with recirculating flow that isolates a volume of water over a known area of bottom sediment were deployed at each site. Direct measurements of SOD using in-situ chambers minimize (1) disturbance and compaction of the sediments, (2) disturbance of the biological community, and (3) alteration of ambient conditions (Murphy and Hicks, 1986).

The SOD chambers (figs. 2 and 3) are open-bottomed, opaque plastic cylinders that are seated and sealed on the river bottom by scuba divers. When seated, each chamber

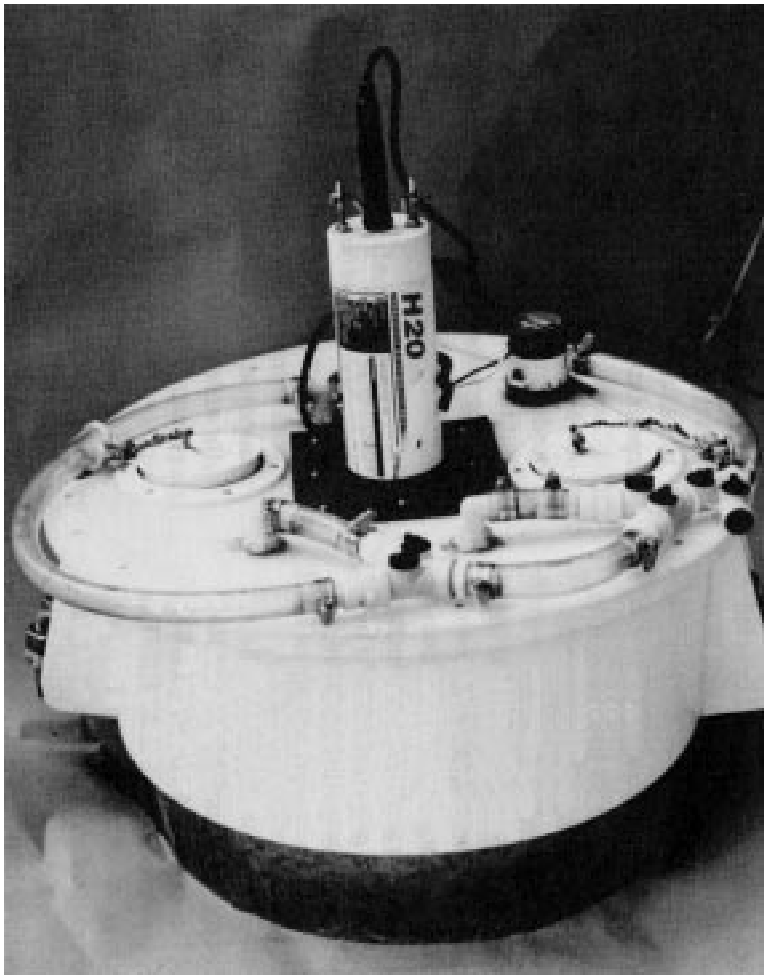

Figure 2. Sediment oxygen-demand chamber.

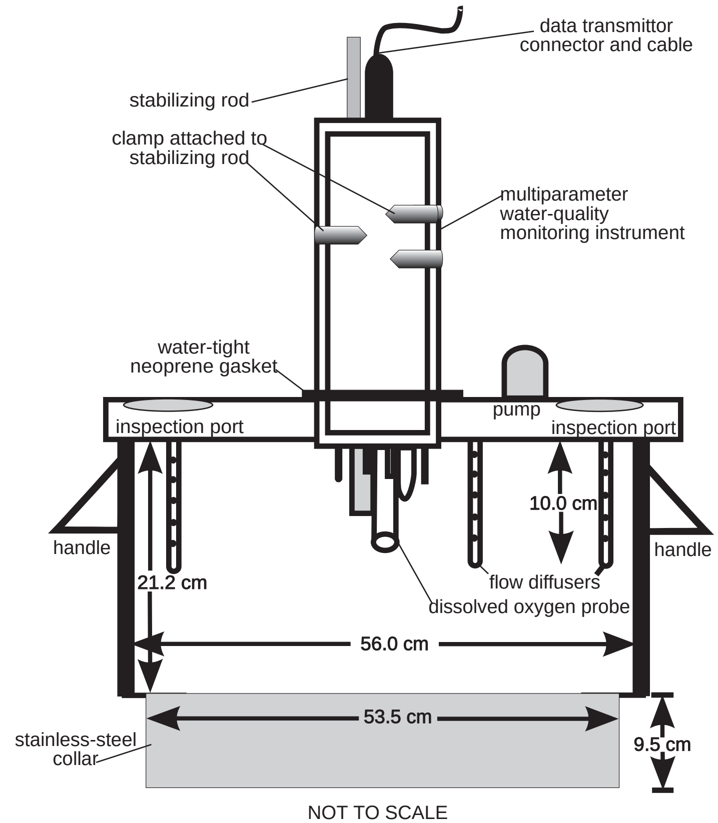

Figure 3. Schematic drawing of sediment oxygen-demand chamber.

contains 52 liters of isolated river water that is slowly recirculated for at least 2 hours over 0.225 square meters of bottom sediment. A Hydrolab multiparameter probe, fitted with a “Lo-Flow” DO membrane, is mounted vertically in the center of the chamber (fig. 2).

The chambers used in this study are based on a design acquired from the ODEQ, which in turn was based on a design by Murphy and Hicks (1986). Dimensions of the internal measuring portion of the chamber are provided in figure 3. The lower portion of the chamber is a stainless-steel collar to assist in bed-sediment penetration when seating the chambers. The water in the chamber is circulated by a bilge pump that pumps at a rate of 1,363 liters per hour (22–23 liters per minute); this rate allows for complete mixing within the chamber. Water flows into the chamber through three diffuser tubes that are designed to allow water to flow while minimizing agitation of bottom sediments. A dye test within the chamber confirmed complete mixing within 2 minutes and a circulating velocity within the chamber of 0.1 to 0.2 ft/s. This fixed mixing rate created complete mixing in the chamber without creating velocities greater than those expected in the study area. Therefore, the measured SOD rates would represent a minimum.

The mean velocity in Newberg Pool during the study period was 0.57 ft/s. Velocities ranged from 0.85 ft/s (RM 48.6 to 46) to 0.48 ft/s (RM 35.7 to 34.4), based on a mean discharge at the Salem gaging station of 6,100 cubic feet per second and travel rates developed by Harris (1968). Assuming a standard velocity profile, the estimated river velocity at 8 inches above the river bottom, a point that would be near the top of the chambers, was 0.35 ft/s.

In Portland Harbor, which is tidally influenced, the flows reverse direction. The net downstream velocity between RM 19 and RM 10 was 0.22 ft/s; between RM 10 and RM 6.4 the net downstream velocity was 0.09 ft/s. The maximum velocities occurred during rising or falling tides and reached 0.5 ft/s. Assuming a standard velocity profile, the water velocity at 8 inches above the river bottom ranged from 0.0 to 0.30 ft/s.

Chamber Deployment

Procedures for deploying SOD chambers were standardized from prior studies in the Tualatin River Basin from 1992 to 1994. The equipment needed to deploy each chamber included a USGS-constructed SOD chamber; a 12 volt battery (to power the pump); and a calibrated Hydrolab multiparameter water-quality instrument programmed to automatically record measurements of DO, temperature, specific conductance, and pH. The DO probe was fitted with a “Lo-Flow” DO membrane, which is minimally affected by variations in sample flow and is suitable for velocities as low as 1 millimeter per second (0.003 ft/s) (Hydrolab Inc., 1991).

Following are the steps used in SOD chamber deployment:

(1) A calibrated Hydrolab multiparameter probe is inserted in the chamber and clamped to the stabilizing rod (figs. 2 and 3).

(2) Near the surface, two scuba divers inspect the submerged chamber to check power, pump circulation, and connections to ensure that all air is removed from the chamber and its associated tubing.

(3) A valve on top of the chamber is adjusted to direct water from within the chamber out into the river. This step is done in preparation for purging the chamber (step 5).

(4) With the pump off and ports open, the chamber is lowered and seated in the bottom sediment by divers. This is done with minimal disturbance to the bottom material. The chamber is left undisturbed for at least 10 minutes to allow any resuspended sediments to settle.

(5) After the settling period, the pump is turned on and the chamber purged. This purge cycle, with the ports open and the valve directing water from inside the chamber out into the river, ensures that

native, near-bottom water fills the chamber and that any remaining resuspended material is pumped out.

(6) Divers return after the chamber has been purged for at least 10 minutes. The valve is adjusted to recirculate water within the chamber and the ports are closed.

(7) The starting time and initial readings are noted. The data loggers are programmed to log readings at 5-minute intervals (readings are also recorded manually at 10-minute intervals). Measurements are made for about 2 hours.

SOD measurements were obtained in triplicate at each site, and the above steps (1–7) were repeated for each chamber deployed.

Water-Column Oxygen Demand

A sample of water was collected near the river bottom and the rate of oxygen depletion was measured. Water samples were collected in 300 ml opaque bottles by scuba divers. This near-bottom water sample was placed in a water bath and DO readings were made using calibrated YSI model 57 and model 58 DO meters equipped with a YSI model 5420A self-stirring probe. DO concentrations were measured at 20-minute intervals over a 2-hour time period.

Sediment Sample Collection and Analysis

Scuba divers collected bottom-sediment samples adjacent to each chamber. An Eckman dredge sampler was carefully pushed into the bottom sediment next to each chamber and the tripping mechanism was manually engaged. Once retrieved, the upper 2 centimeters of bottom material were subsampled for analysis. Sediment-sample analysis was performed by the U.S. Geological Survey Sediment Laboratory at the Cascade Volcano Observatory in Vancouver, Washington. Sediment samples were analyzed for percent water, organic content (Fishman and Friedman, 1989), and percent sand (particle size greater than 0.062 mm) (Guy, 1969).

Calculation of Sediment Oxygen Demand

Two hours was a sufficient time period for a representative SOD rate to be established in the chambers. Rapid decreases in DO within the chambers were occasionally noticed in the first 10 to 20 minutes of the assay. This was attributed to the slight disturbance of the bottom sediment caused by insertion of the SOD chambers. When this occurred, the rate always stabilized after an initial nonlinear loss of oxygen. Only the data obtained after that initial period were used in the calculations of SOD rates. A representative oxygen-loss curve for the in-situ field measurements is presented in figure 4. The slope of the oxygen-depletion line is used to calculate the SOD:

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

where SOD is the sediment oxygen-demand rate in $g/m^2 \cdot day$, b is the slope of the oxygen-depletion curve in milligrams per liter per minute ($mg/L \cdot minute$), V is the volume of the chamber in liters, A is the area of bottom sediment covered by the chamber in square meters, and 1.44 is a units-conversion constant. Volume corrections were made when insertion of the chambers was less than or more than the ideal (insertion of the entire stainless-steel collar on the chamber constituted an ideal seating, figs. 2 and 3).

Measured SOD rates were corrected to $20^{o}C$ using the following equation:

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

where SOD_{20} is the SOD at $20^{o}C$, and SOD_T is the measured SOD at temperature T (^{o}C) (Thomann and Mueller, 1987).

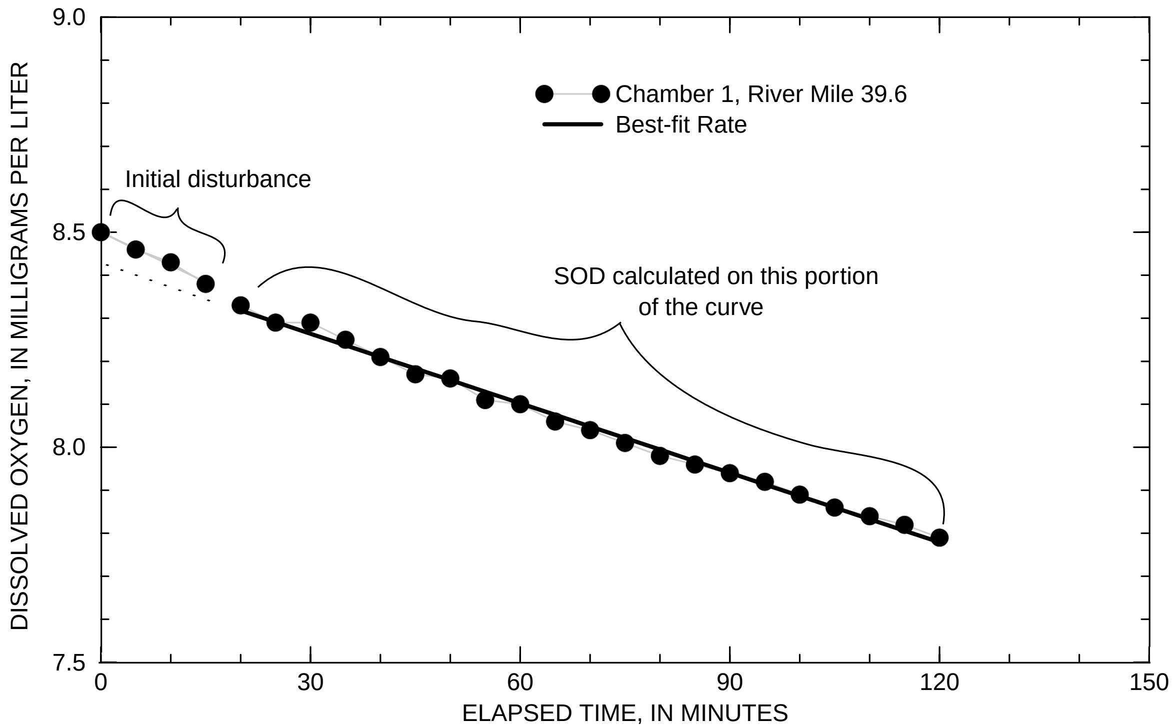

Figure 4. Representative sediment oxygen-demand (SOD) curve.

RESULTS AND DISCUSSION

The results of SOD measurements and bed-sediment analyses at selected sites in the Willamette River are given in table 1.

Sediment Characteristics

Sediment samples were collected near each chamber and analyzed for percent water, percent sand, and percent organics. The sand content ranged from 0.1 to 6.2 percent and averaged 1.8 percent. The organic content ranged from 1.4 to 9.6 percent and averaged 5.6 percent. Results of the sediment analyses are given in table 1.

River morphology enhances deposition both at the upstream end of Newberg Pool and downstream from RM 10 (Rickert and others, 1976). Divers found that the areas where chamber insertion was especially easy (where, in fact, they had to be careful not to overinsert the chambers) were in these depositional areas. This was noted at RM's 50.5, 49, 15.7, 13.2, 6.3, and 3.1. The lab results show a low variability in the overall sand content of the bottom sediments within the study area. Divers noted a layer of fine, light, flocculent material at all sites, including those sites where chamber insertion was difficult or impossible, such as areas containing gravels or cobbles. Although the SOD chambers could not be used in areas with gravels and cobbles, it should not be assumed that these substrates have zero SOD. The flocculent layer on top of these substrates, and in interstitial spaces, may exert an oxygen demand on the water column. It is reasonable to assume, however, that the SOD associated with gravels and cobbles is less than the SOD associated with the fine-grained sediments, where the chambers could be inserted.

Table 1. Measured sediment oxygen demand and bed sediment characteristics at selected sites in the Willamette River, Oregon, August 1994

[SOD_T = sediment oxygen demand measured at river water temperature; SOD_{20} = sediment oxygen demand corrected to 20 degrees Celsius (^oC) using $SOD_{20} = SOD_T / 1.065^{T-20}$ where T = water temperature in ^oC; $g/m^2 \cdot day$, grams of oxygen per square meter per day]

Site Number	River mile	Location name	Date	Chamber number	Depth feet	Percent distance from left bank	SOD_T $g/m^2 \cdot day$	River temperature ^oC	SOD_{20} $g/m^2 \cdot day$ (calculated)	Percemt moisture	Percent sand >0.062mm	Percent organic material
1	50.5	Newberg	08/15/94	1	22	60	2.1	21.5	1.9	58.4	0.6	5.5
				2	18	75	4.1	21.5	3.7	42.7	0.6	2.8
				3	17	70	3.0	21.5	2.7	61.3	0.9	6.4
2	49.0	Upstream from Highway 219	08/15/94	1	18	60	2.2	21.5	2.0	57.8	1.2	7.1
				2	15	70	2.5	21.5	2.3	59.9	0.9	6.2
				3	15	80	2.7	21.5	2.5	55.7	1.5	5.6
3	45.0	Downstream from Champoeg Creek	08/16/94	1	18	55	2.3	21.5	2.1	44.3	2.2	4.7
				2	18	65	1.9	21.5	1.7	54.1	1.2	5.6
				3	18	80	1.7	21.5	1.6	49.2	1.9	5.2
4	39.6	Downstream from Corral Creek	08/16/94	1	28	40	1.8	22.0	1.6	52.8	1.3	6.0
				2	27	20	2.4	22.0	2.1	53.0	1.7	5.7
				3	23	10	2.0	22.0	1.8	58.3	0.9	6.1
5	35.5	Downstream from Molalla River	08/18/94	1	9	15	1.6	22.0	1.4	57.3	1.0	5.3
				2	7	10	2.1	22.0	1.8	52.1	0.4	4.4
				3	10	20	1.7	22.0	1.5	41.6	1.3	4.2
6	31.5	Downstream from Willow Island	08/17/94	1	7	15	2.1	22.5	1.8	30.9	3.4	2.3
				2	8	10	2.2	22.5	1.9			
				3	8	10	1.5	22.5	1.3	22.8	2.6	1.4
7	28.0	Mouth of Tualatin River	08/17/94	1	22	20	2.3	22.0	2.0	38.9	2.2	4.1
				2	17	20	2.5	22.5	2.1	25.2	4.8	2.3
				3	22	15	2.2	22.5	1.9	28.7		1.9
8	24.3	Downstream from Clackamas River	08/11/94	1	11	20	3.0	21.5	2.7	31.1	6.2	2.3
				2	10	15	3.2	22.0	2.8	28.0	4.9	1.6
				3	9	15	1.6	22.0	1.4	45.9	3.8	6.0

Table 1. Measured sediment oxygen demand and bed sediment characteristics at selected sites in the Willamette River, Oregon, August 1994—Continued

[SOD_T = sediment oxygen demand measured at river water temperature; SOD_{20} = sediment oxygen demand corrected to 20 degrees Celsius (°C) using $SOD_{20} = SOD_T / 1.065^{T-20}$ where T = water temperature in °C; $g/m^2 \cdot day$, grams of oxygen per square meter per day]

Site Number	River mile	Location name	Date	Chamber number	Depth feet	Percent distance from left bank	SOD_T $g/m^2 \cdot day$	River temperature °C	SOD_{20} $g/m^2 \cdot day$ (calculated)	Percemt moisture	Percent sand >0.062mm	Percent organic material
9	19.4	Upstream from Elk Island	08/11/94	1	23	20	1.5	22.0	1.3	52.0	2.6	8.1
				2	20	15	2.2	22.0	1.9	54.4	1.4	5.1
				3	19	15	1.9	22.0	1.7	44.8	2.7	4.7
10	17.0	Upstream from Sellwood Bridge	08/08/94	1	23	25	2.3	22.5	2.0	56.4	1.3	6.6
				2	22	25	2.1	22.5	1.8	77.2	0.8	6.4
				3	18	20	3.2	22.5	2.7	57.9	1.2	6.3
11	15.7	Upstream from Ross Island	08/10/94	1	24	80	3.1	22.0	2.7	60.3	1.2	8.8
				2	22	85	2.5	22.5	2.1	56.8	2.0	9.9
				3	22	80	3.0	22.5	2.6	57.9	2.1	9.5
12	13.2	Upstream from Hawthorne Bridge	08/10/94	1	18	10	2.7	22.5	2.3	50.5	2.0	6.3
				2	19	15	2.7	23.0	2.2	59.0	0.9	6.6
				3	18	10	2.1	22.5	1.8	49.0	0.9	5.4
13	8.1	Below Swan Island	08/12/94	1	26	85	1.6	22.5	1.4	23.6	4.3	1.8
				2	28	90	2.0	22.5	1.7	35.3	3.1	3.4
				3	26	85	1.8	23.0	1.5	30.4	3.6	2.1
14	6.3	Upstream from St. Johns Bridge	08/09/94	1	42	15	3.0	23.0	2.5	73.3	0.3	9.3
				2	42	20	1.9	22.5	1.6	71.7	0.3	9.2
				3	43	15	5.0	23.0	4.1	74.8	0.1	9.6
15	3.1	Near Multnomah Channel	08/09/94	1	40	85	2.3	22.5	2.0	70.3	0.2	8.2
				2	40	85	2.4	22.5	2.0	70.9	0.3	8.1
				3	40	90	2.6	22.5	2.2	65.3	0.3	7.9

Sediment Oxygen Demand

Measured SOD rates ranged from 4.1 g/m^2 · day at RM 6.3 (in a depositional area of the river) to 1.3 g/m^2 · day at RM 31.5 and RM 19.4, and averaged 2.1 g/m^2 · day (table 1). The overall variability of measured SOD rates (corrected to 20^{o}C) was lower than expected (standard deviation = 0.6 g/m^2 · day, n=45). In particular, the variability was especially low between RM 45 and RM 28. In this stretch of river, the SOD rate (corrected to 20^{o}C) averaged 1.8 and had a standard deviation of 0.3 g/m^2 · day (n=15). The SOD rate measured in Newberg Pool averaged 2.0 g/m^2 · day; the SOD rate in Portland Harbor averaged 2.1 g/m^2 · day. Compared with historical SOD rates measured by Thomas (1970), SOD rates measured in fine-grained sediments of the Willamette River during this study were remarkably constant, having very little difference by river mile (fig. 5) and indicating little impact from industrial or municipal point sources of organic matter.

DO concentrations in the water column ranged from 6.4 to 8.8 mg/L for the entire study area. Although vertical gradients of DO were observed at some sites, the near-bottom water was always oxygenated adequately for the SOD analysis (the lowest DO reading near the bottom was 6.4 mg/L).

Water samples near the chambers were collected by the divers and the rate of oxygen depletion was measured. These data were collected to correct the SOD values for any oxygen demand associated with the water column. However this correction was not applied for the following reasons:

(1) In all cases, the oxygen depletion observed in the 2-hour period was less than the precision of the instruments (± 0.1 mg/L) and can only be considered an estimate. Applying these estimates of water-column oxygen demand to the calculation of SOD would affect the results by less than 3 percent, and thus is not warranted.

(2) Analysis of a 5-day biochemical oxygen demand (BOD) performed during this sampling period by ODEQ as part of their routine river monitoring program indicated very little BOD in the water column. Samples collected on August 29, 1994 showed the 5-day BOD to be 0.5 mg/L in Newberg Pool at Highway 219 (RM 48) and 1.1 mg/L in Portland Harbor at Hawthorne Bridge (RM 13). This rate constitutes a negligible demand for a 2-hour period (< 0.02 mg/L).

SOD rates in the Tualatin River measured during the summer seasons of 1992–94 are similar to the SOD results obtained during this study in the Willamette River. Ninety-six measurements in the Tualatin River were made between May and October. Values fluctuated little between the early and late season measurements. The measured SOD rates (corrected to 20^{o}C) ranged from 0.7 g/m^2 · day to 5.2 g/m^2 · day, with a mean of 2.2 g/m^2 · day (S.A. Rounds and others, USGS, unpub. data, 1995).

During the 1969 study of SOD in the Willamette River (Thomas, 1970), measurements were taken in April, July, and September at 9 sites between Newberg and Portland. Maximum SOD rates were observed in July, with a value of 12.6 g/m^2 · day near RM 38 at 18^{o}C, 19.5 g/m^2 · day near RM 21 at 16^{o}C, and 9.8 g/m^2 · day near RM 13 at 16^{o}C. Further examination of the sediments showed that these high rates were indicative of sludge deposits from pulp and paper mill discharges. The organic material in these sludge deposits was probably labile, decomposing at a faster rate than the background organic material. In September these rates were 46 percent lower due to oxidative depletion of the sludge in the sediments. From spring to fall there was a 22 percent reduction in the organic carbon content. Three of the sites sampled were not affected by these sludge deposits. With the results from those three sites, Thomas estimated SOD rates of the natural bottom material in the Willamette River to be less than 2.3 g/m^2 · day.

The SOD rates measured in the Willamette River in 1994 (2.1 g/m^2 · day) are

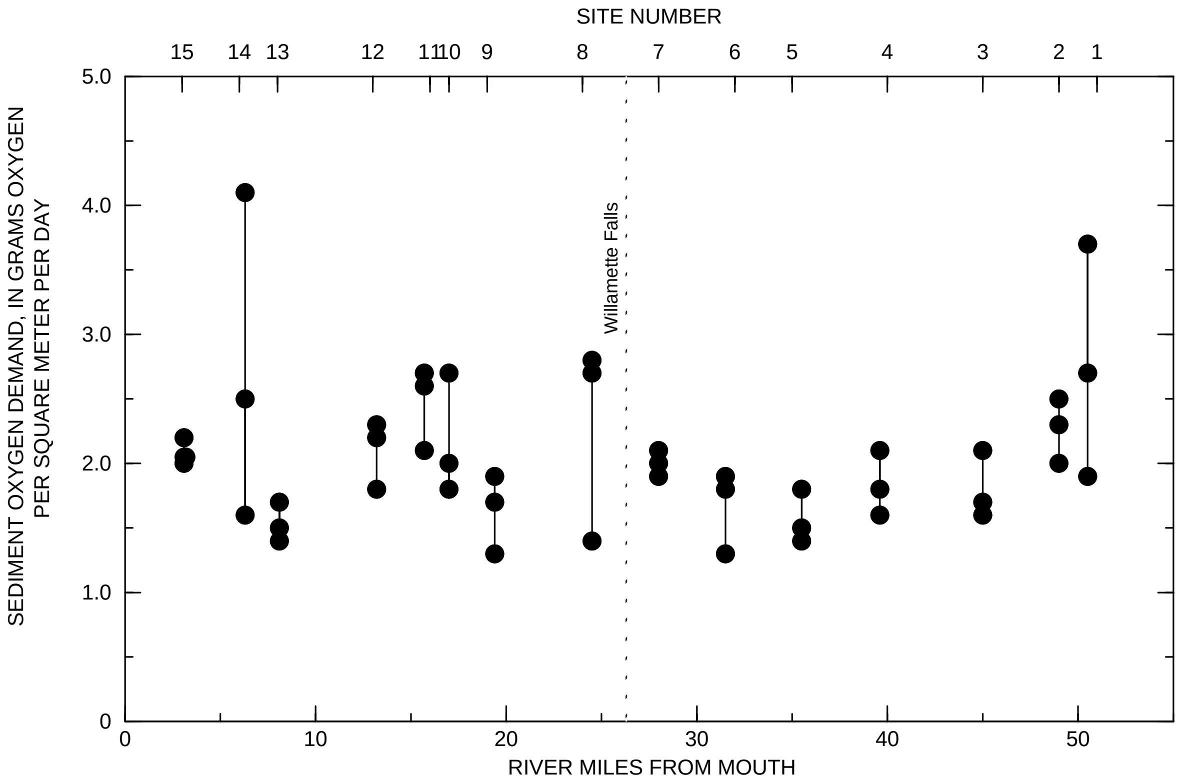

Figure 5. Sediment oxygen-demand measurements in the Willamette River (three measurements per site), corrected to 20 degrees Celsius.

similar to those recently measured in the Tualatin River (2.2 g/m^2 · day) and to those measured for natural bottom material in the Willamette River in 1969 (< 2.3 g/m^2 · day). Sludge deposits and high SOD rates like those encountered in 1969 were not observed during the 1994 survey of SOD in the Willamette River. The natural conditions and processes apparently have remained relatively constant in the Willamette since 1969.

One goal of this study was to quantify the SOD as a function of different sediment types to determine whether the two are correlated. For instance, a higher SOD might be associated with sediment with a higher content of organic material; a lower SOD might be associated with a high percentage of sand. Although the measured organic material content varied by a factor of 8 (from 1.4 to 9.9 percent), no statistically significant correlations between the measured SOD and sediment characteristics was found. A review by the National Council of the Paper Industry for Air and Stream Improvement, Inc., (1978) found that many previous studies reported poor correlation of oxygen consumption with organic content. These studies suggested that the availability of the organic matter to the overlying water, rather than the absolute amount of that material, is of most importance. For instance, activity of macroinvertebrates has been reported to increase the uptake rate by increasing the sediment surface area (National Council of the Paper Industry for Air and Stream Improvement, Inc., 1978).

The SOD chambers could not be deployed in all bottom materials found in the study area. A layer of fine, light, flocculent material was noted at all sites, including those areas where the SOD chambers could not be inserted such as those with large gravels. If organic, this flocculent material would exert some sediment oxygen demand even in these firmer, rocky substrates.

The Eckman dredge was deployed a total of 118 times during the field reconnaissance. Site selection for the SOD chambers was largely determined by whether the bottom material where the dredge was deployed was soft enough for chamber insertion. It was clear that the SOD chambers could not be inserted into bottom sediment composed primarily of large gravels or cobbles. For Newberg Pool, deployment of the SOD chambers was possible at about 45 percent of the sites visited. In the Portland Harbor, deployment of the chambers was possible at about 70 percent of the sites visited. Based on these results, the SOD may be biased slightly high because sites were selected only where chamber deployment was possible.

These data can be used to estimate reachwide SOD rates for modeling dissolved oxygen concentrations in the lower Willamette River. To calculate a reachwide SOD rate (SOD_{reach}), a range of SOD rates must be estimated for the river where the chambers could not be deployed (SOD_{hard}). These estimates are used in the following equation:

$$SOD_{reach} = f_{soft} \times SOD_{soft} + (1 - f_{soft}) \times SOD_{hard} \quad (3)$$

where f_{soft} is the percentage of river bottom where SOD chambers could be deployed, and SOD_{soft} is the SOD rate (corrected to 20°C) measured in those areas with soft bottom sediment.

Applying equation 3 to Newberg Pool, SOD_{reach} falls between 0.9 and 2.0 $g/m^2 \cdot day$, assuming that SOD_{soft} equals 2.0 $g/m^2 \cdot day$, f_{soft} equals 0.45 and SOD_{hard} ranges between zero and 2.0 $g/m^2 \cdot day$. A value of zero for SOD_{hard} is probably unrealistically low based on the observation that soft, flocculent material was observed on top of and in the interstitial spaces of the gravels and cobbles of the lower Willamette River. Conversely, a value of 2.0 $g/m^2 \cdot day$ for SOD_{hard}, the SOD rate measured in the soft bottom sediment of Newberg Pool, is probably too high. It is reasonable to assume that the SOD in areas covered by gravels and cobbles is less than the SOD in areas covered by fine-grained sediment. Consequently, for purposes of modeling dissolved oxygen concentrations, a reachwide SOD rate of 1.4 (± 0.5) $g/m^2 \cdot day$, the midpoint of the calculated range, is probably a reasonable estimate for the Newberg Pool.

Applying equation 3 to the Portland Harbor, SOD_{reach} falls between 1.5 and 2.1 g/m^2 day, assuming that SOD_{soft} equals 2.1 $g/m^2 \cdot day$, f_{soft} equals 0.7 and SOD_{hard} ranges between zero and 2.1 $g/m^2 \cdot day$. Based on the same arguments given above, 1.8 (± 0.3) $g/m^2 \cdot day$ is probably a reasonable estimate for a reachwide SOD rate in the Portland Harbor.

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