# Sediment Oxygen Demand in the Tualatin River Basin, Oregon, 1992–96

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## CONVERSION FACTORS

| Multiply | By | To obtain |
|---|---|---|
| inch (in) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| yard (yd) | 0.9144 | meter (m) |
| square foot ($ft^2$) | 0.09290 | square meter ($m^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| cubic foot ($ft^3$) | 0.02832 | cubic meter ($m^3$) |
| cubic foot ($ft^3$) | 28.32 | liter (L) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| ounce, avoirdupois (oz) | 28.35 | gram (g) |
| pound, avoirdupois (lb) | 0.4536 | kilogram (kg) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=1.8\,C+32$$

**Concentrations of chemical constituents** in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

# Sediment Oxygen Demand in the Tualatin River Basin, Oregon, 1992–96

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## Abstract

Sediment oxygen demand (SOD) rates were measured by U.S. Geological Survey (USGS) personnel at 20 stream sites in the Tualatin River Basin from 1992 through 1996 as part of an investigation into the sources and sinks of dissolved oxygen in the Tualatin River. During the low-flow summer periods of 1992 through 1994, 97 measurements were collected at 9 sites on the main stem of the river between river miles (RMs) 5.5 and 43.2. During the low-flow summer periods of 1995 and 1996, 28 measurements of SOD were collected at 11 sites on 8 tributaries of the Tualatin River. All SOD rates were measured with in-situ benthic chambers designed to monitor the loss of dissolved oxygen in a known volume of water circulating above a known area of minimally disturbed stream sediment.

For main-stem Tualatin River sites, the observed SOD rate ranged from 0.6 to 4.4 grams of oxygen per square meter per day ($g/m^2d$) with a median of 2.3 $g/m^2d$. In the tributaries, the measured SOD rate ranged from 0.2 to 10.9 with a median of 3.6 $g/m^2d$. These rates are in the range of those reported for other sites in Oregon and across the United States. Most of the variation in the measured SOD rates was likely due to heterogeneities in the bed sediment.

Statistical comparisons show that the rates measured at the tributary sites are significantly larger than those measured in the main stem. Within the main stem, the rates measured at sites in the meander reach of the river were not significantly different from those measured in the reservoir reach. Similarly, no difference was found when the sites affected by the cycle of phytoplankton bloom and die-off were compared to those unaffected by phytoplankton. Only one site on the main stem, RM 5.5, was found to have an SOD rate that was significantly higher than that found at the other main-stem sites. Algal detritus may contribute to the elevated rate at that site, but other factors such as the rate of sediment accumulation could also account for the increased rate.

## INTRODUCTION

### Background

Ample dissolved oxygen (DO) is critical to the health of fish and other aquatic organisms. The Oregon Department of Environmental Quality (ODEQ), in order to protect those organisms and support other designated beneficial uses of surface waters throughout Oregon, has written standards for the minimum amount of dissolved oxygen in such waters. Despite supporting a wide variety of aquatic life, the Tualatin River and its tributaries sometimes violate the State of Oregon dissolved oxygen standard. These violations normally occur during the low-flow summer period (May through October); a previous study of the Tualatin River has shown that the winter high-flow period generally is characterized by dissolved oxygen levels that are well above the standard (Kelly, 1996).

In order to properly manage the Tualatin River and avoid future violations of the State dissolved oxygen standard, it is imperative to understand the relative magnitudes of the various sources and sinks of dissolved oxygen in the river. Possible sources of DO include reaeration (exchange with the atmosphere) and photosynthetic production. Potentially important sinks of DO include water-column biochemical oxygen demand (BOD), sediment oxygen demand (SOD), ammonia nitrification, and the respiration of phytoplankton and zooplankton.

SOD is a combination of all of the oxygen-consuming processes that occur at or just below the sediment/water interface. SOD is partly due to biological processes and partly due to chemical processes. Most of the SOD at the surface of the sediment is due to the biological decomposition of organic material and the bacterially facilitated nitrification of ammonia, while the SOD several centimeters into the sediment is often dominated by the chemical oxidation of species such as iron, manganese, and sulfide (Wang, 1980; Walker and Snodgrass, 1986).

SOD has been found to be an important sink for dissolved oxygen in a wide variety of surface waters. In Oregon, Thomas (1970) measured SOD rates at nine sites in the lower Willamette River and found rates as high as 19.5 $g/m^2d$ at sites heavily impacted by pollution. Caldwell and Doyle (1995) recently found SOD rates in the same reach of the lower Willamette River to range from 1.3 to 4.1 $g/m^2d$, indicating a substantial improvement in water quality over 25 years. These rates are still high enough, however, to be important sinks for dissolved oxygen (Tetra Tech, 1995).

Prior to 1992, the magnitude of the SOD rate in the Tualatin River was unknown. This unknown SOD was thought to be an important part of the oxygen budget in the Tualatin River, and because the lower reaches of the river often produced very large phytoplankton blooms (greater than 100 µg/L of chlorophyll-*a*), it had been hypothesized that the SOD rate in that reach of the river would be heavily influenced by the decomposition of settling algal detritus. Therefore, it was thought that reducing the amount of phytoplankton would result in a concomitant reduction in the impact of the SOD on DO concentrations.

The Unified Sewerage Agency (USA) of Washington County is one of the designated management agencies for the Tualatin River. In order to manage the river for dissolved oxygen, it is necessary for USA managers to know the magnitude of the SOD rate, how it varies spatially and temporally, and whether that rate is influenced by decomposing algal detritus. An ongoing USGS/USA cooperative investigation into the sources and sinks of dissolved oxygen in the Tualatin River was started in 1990. This study of SOD was part of that larger investigation.

## Purpose and Scope

This report discusses the USGS measurements of SOD in the Tualatin River Basin. Specifically, this investigation of SOD in the Tualatin River Basin was designed to:

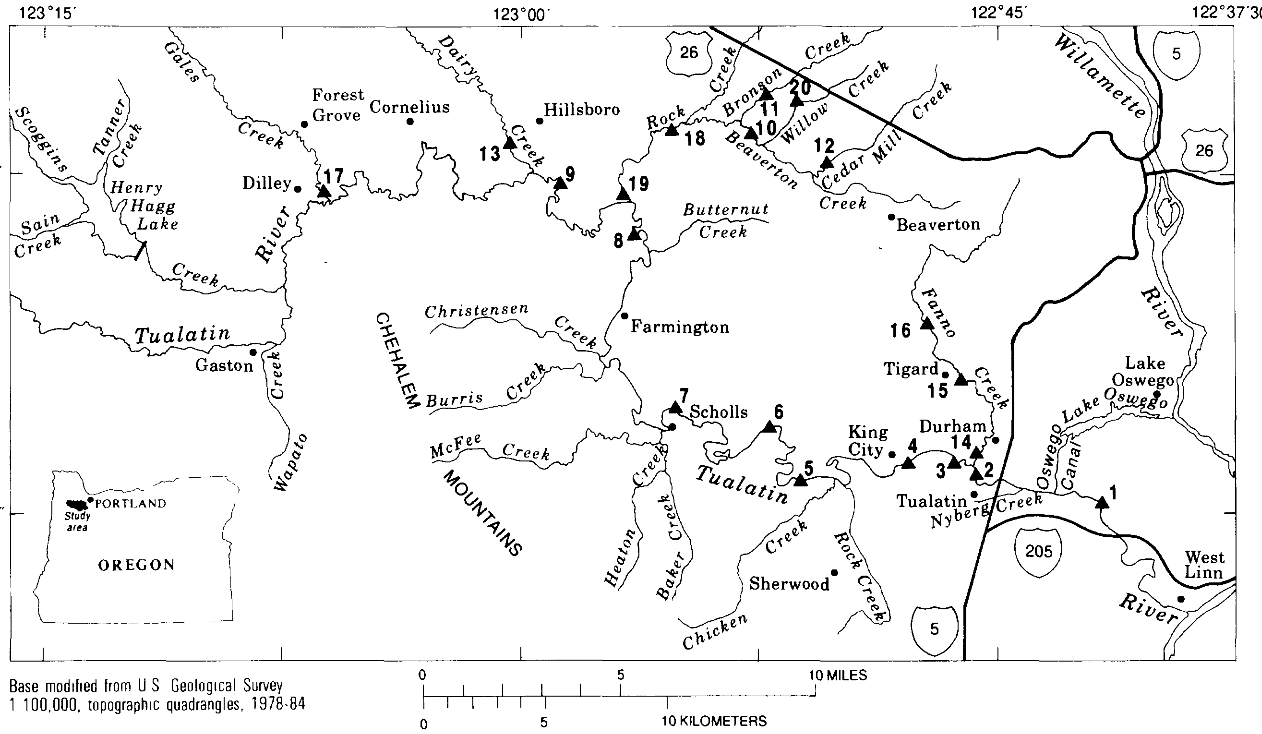
- determine the magnitude of the SOD rate in the main stem and the tributaries,
- determine the spatial and temporal variability of the SOD rate in the main stem,
- determine the influence of the river flow regime on the SOD rate, and
- determine the influence of phytoplankton on the SOD rate.

These objectives were accomplished by measuring the SOD rate at various locations and at different times during the low-flow summer period. Other measures of water quality necessary to this study, such as chlorophyll-*a* concentrations, were collected by USA as part of a routine monitoring program. The investigation was restricted to the low-flow period between May 1 and October 31. Throughout this report, all references to algae refer only to phytoplankton.

## Study Area

The Tualatin River Basin is located in northwestern Oregon on the west side of the Portland metropolitan area (fig. 1). Its 712 square mile drainage area supports a growing population of more than 320,000 and a wide variety of forest-related, agricultural, industrial, and residential uses. The basin is bounded on the west by the Coast Range, on the north and east by the Tualatin Mountains, and on the south by the Chehalem Mountains and by Parrett Mountain. The Tualatin River flows generally from west to east and joins the Willamette River near West Linn. River discharge generally reflects the region's climate and is often augmented during the summer with releases from Henry Hagg Lake. Most of the precipitation falls as rain during the November to April period, resulting in high winter flows on the order of thousands of cubic feet per second ($ft^3/s$). The May through October period is much drier; streamflow decreases to its lowest levels in July, August, and September, and typically is less than 200 $ft^3/s$ during that period.

The main stem of the Tualatin River is 79.4 miles long and has its origin in the forested Coast Range on the western edge of the basin. In its head-




**EXPLANATION**

▲5 **Sampling site and map number** — See table 1

| Map number | Tualatin River sites |
|---|---|
| 1 | Tualatin River at Stafford Road near Lake Oswego, Oregon (RM 5.5) |
| 2 | Tualatin River at Boones Ferry Road at Tualatin, Oregon (RM 8.7) |
| 3 | Tualatin River at Cook Park near Tigard, Oregon (RM 10.0) |
| 4 | Tualatin River near Highway 99W Bridge near King City, Oregon (RM 11.7) |
| 5 | Tualatin River at Elsner Road near Sherwood, Oregon (RM 16.2) |
| 6 | Tualatin River at Lakeside Reclamation near Scholls, Oregon (RM 20.3) |
| 7 | Tualatin River at Highway 210 Bridge near Scholls, Oregon (RM 26.9) |
| 8 | Tualatin River at Meriwether irrigation pump near Hillsboro, Oregon (RM 36.8) |
| 9 | Tualatin River at River Mile 43.2 near Hillsboro, Oregon (Jackson Bottom) |

| Map number | Tualatin River tributary sites |
|---|---|
| 10 | Beaverton Creek at Arleda Park near Hillsboro, Oregon |
| 11 | Bronson Creek at Walker Road at Hillsboro, Oregon |
| 12 | Cedar Mill Creek near Jenkins Road at Beaverton, Oregon |
| 13 | Dairy Creek at Dairy Creek Park at Hillsboro, Oregon |
| 14 | Fanno Creek at Durham City Park at Durham, Oregon |
| 15 | Fanno Creek at Fanno Creek Park at Tigard, Oregon |
| 16 | Fanno Creek at Englewood Park at Tigard, Oregon |
| 17 | Gales Creek at Zurcher irrigation pump near Forest Grove, Oregon |
| 18 | Rock Creek near Southeast 59th Avenue at Hillsboro, Oregon |
| 19 | Rock Creek at Rock Creek Wastewater Treatment Plant at Hillsboro, Oregon |
| 20 | Willow Creek at Apollo Ridge Park at Beaverton, Oregon |

**Figure 1**. Location of sediment oxygen demand sampling sites in the Tualatin River Basin, Oregon. (RM, river mile.)

water reach (RM 79.4 to 55.3), the river is narrow and drops in elevation rapidly with an average slope of 74 feet per mile. Downstream of that reach, the river reaches the bottom of the valley and begins to meander through a predominantly agricultural area. This meander reach extends from RM 55.3 to 33.3; the river there is roughly 50 feet wide and has an average slope of 1.3 feet per mile. From the meander reach, the river flows into its reservoir reach (RM 33.3 to 3.4), spreading out to about 150 feet wide and slowing down with an average slope of only 0.08 feet per mile, depending on the discharge rate. At RM 3.4, the river enters a pool and riffle reach and loses 13 feet of elevation per mile before reaching its confluence with the Willamette River. From the lower end of the reservoir reach to its mouth, the river flows through a mixture of agricultural and urban landscapes.

Major tributaries of the Tualatin River include Scoggins, Gales, Dairy, Rock, and Fanno Creeks (fig. 1). Smaller streams that eventually feed into the river include Beaverton, Bronson, Willow, and Cedar Mill Creeks, among many others. The Scoggins and Gales Creek drainages are primarily forested. Dairy Creek flows primarily through agricultural land. The Rock Creek drainage is mixed, with a large urban influence. Fanno, Beaverton, Bronson, Willow, and Cedar Mill Creeks all flow through predominantly urban areas.

Site locations were selected using several criteria. Main-stem sites were selected for (a) adequate distribution throughout both the meander and reservoir reaches, (b) proximity to monitoring stations, and (c) access considerations such as landowner permission and safety. Tributary sites were selected for (a) sufficient water depth to submerge the measurement chamber, (b) a variety of upstream land uses, (c) an adequate areal distribution, and (d) access considerations.

A number of SOD measurement sites (sites 1–7, fig. 1) were selected in the reservoir reach of the main stem for two reasons. First, that reach is the location of the largest phytoplankton populations. Second, the long residence time and low reaeration rate in that reach tend to increase the impact of those processes that consume oxygen in the water column and at the sediment/water interface; therefore, the SOD was expected to be an important part of the dissolved oxygen budget there. Two sites (8 and 9, fig. 1) were chosen in the meander reach as controls against the influence of the phytoplankton; the algal population in the meander reach typically is very small. Finally, a number of sites (10–20, fig. 1) were chosen on many of the tributaries in order to compare the effects of stream order. At most of the sites, ground water was found to be slowly discharging to the stream at the time of the measurement.

The sediments at all sites in the meander and reservoir reaches of the main stem and most sites on the tributaries are composed mainly of silt and clay-sized particles. Only Gales Creek showed evidence of much sand (visual inspection). In several short reaches of the main-stem Tualatin River, the river bottom does have large rocks and cobbles where the river flows over bedrock sills. Most of the river bed, however, has a clayey bottom that typically is covered with several centimeters to several feet of loose silt embedded with detrital material such as leaves, twigs, and plant material. The river is often blocked by logjams in many locations; even where such logs are not visible from the surface, they are common on the river bed. In some places, the clayey bottom is swept clear of silt by the flowing water. In low-velocity depressions, very fine-grained detrital materials tend to accumulate.

## Acknowledgments

This investigation benefited greatly from a number of people and organizations. We gratefully acknowledge the scientific collaboration and financial contributions of the Unified Sewerage Agency of Washington County and the assistance of John Jackson (USA), Janice Miller (USA), Jan Wilson (USA) and Larry Caton (ODEQ). Measurements in the main stem were assisted by USGS scuba divers Dennis Lynch, Jim Poole, Dave Carlson, Dan Zimmerman, Kurt Carpenter, Jim Caldwell, and Ken Skach; additional assistance was provided by Tamara Wood, Richard Norris, Matt Johnston, Bernadine Bonn, Kris Keller, and volunteers Matt Leve and Tirian Mink. Access to sites on the Tualatin River and its tributaries through private property was kindly given by Howard Grabhorn (Lakeside Reclamation), Jim Peterson (Meriwether National Golf Course), Tim Miller (Roamer's Rest), Darrell Vandehey (Reser's Fine Foods), Jeffery Harris, the Tualatin Hills Park

and Recreation District, USA, and the Cities of Hillsboro, Tigard, and Durham.

## METHODS AND PROCEDURES

### Sediment Oxygen Demand Chambers

In-situ SOD chambers with recirculating flow are designed to isolate a known volume of water over a known area of bottom sediment so that the oxygen loss over time may be monitored with minimal (a) disturbance and compaction of the sediments, (b) disturbance of the biological community, and (c) alteration of ambient conditions (Murphy and Hicks, 1986).

The SOD chambers used in this investigation (figs. 2 and 3) are open-bottomed opaque plastic cylinders that are designed to seat and seal on the river bottom. Scuba divers deployed SOD chambers in the main stem of the Tualatin River where water depth at several sites exceeded 15 feet. SOD measurements in the tributary streams did not require divers. Once seated, each chamber isolates about 52 liters of river water that is then slowly recirculated for at least 2 hours over 0.225 square meters of bottom sediment. A calibrated Hydrolab™ multiparameter probe, fitted with a "Lo-Flow" dissolved oxygen membrane, is mounted vertically in the center of the chamber (fig. 3).

The chambers used in this study are based on a design by the ODEQ, which in turn was based on a design by Murphy and Hicks (1986). In 1992, a closed-bottom, "blank" chamber was also used. This chamber was designed to isolate a volume of near-bottom river water without allowing that water to interact with the bottom sediments. The purpose of this closed-bottom chamber was to measure the rate of oxygen depletion in the water column as a "blank" correction. Any oxygen depletion measured in the blank would be subtracted from the loss measured in the open-bottom chamber to correct for this water-column oxygen demand. Due to the low water-column oxygen demand measured in 1992, however, the subsequent use of a closed-bottom chamber was determined to be unnecessary.

Dimensions of the internal measuring part of the chamber are provided in figure 3. The lower part of the open-bottom chamber has a stainless-steel collar to assist in bed sediment penetration when seating the chambers. The closed-bottom chamber has identical dimensions, except it has no collar and has an opaque plastic bottom with two inspection ports which, when opened, facilitated the lowering of the chamber through the water column to the river bed. When the closed-bottom chamber was near but not on the river bed, divers would close the inspection ports and then place it on the river bottom. The chamber would remain at the bottom of the river for the 2-hour measuring period.

During the measurement period, the water in each chamber is circulated by a bilge pump, powered by a 12-volt rechargeable gel-cell battery, at a rate of 1,360 liters per hour (23 liters per minute). Water is withdrawn from the chamber by the pump and then injected into the chamber through three separate diffuser tubes; this design allows for good mixing of the isolated water with minimal suspension of the 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 range of mixing velocities resulted in thorough mixing in the chamber with velocities on the order of those expected in the study area. The "Lo-Flow" membrane on the Hydrolab™ is minimally affected by variations in sample flow and is suitable for velocities as low as 0.003 ft/s (Hydrolab Inc., 1991).

A number of researchers have noted that the actual SOD rate may depend on the degree of turbulence in the water column and that the mixing velocity produced in an in-situ benthic chamber therefore should be controlled to match that near the sediment/water interface outside the chamber (Murphy and Hicks, 1986; NCASI, 1978 and 1979; Parkhill and Gulliver, 1997). Although the mixing velocity can be important when the rate of oxygen utilization in the sediment exceeds the rate at which oxygen in the overlying water column can be delivered, it is also true that when the rate of oxygen utilization in the sediment is low and the mixing velocity is sufficient to eliminate concentration gradients near the sediment/water interface, the SOD rate will not depend on the mixing velocity (Parkhill and Gulliver, 1997). The effect of variations in the chamber mixing velocity will be studied in more detail in future investigations, but preliminary data from the SOD measurements in 1996 at several Tualatin River tributary sites indicate that velocity variations below the normal operating range of 0.1 to 0.2 ft/s do not influence the measured SOD rate.

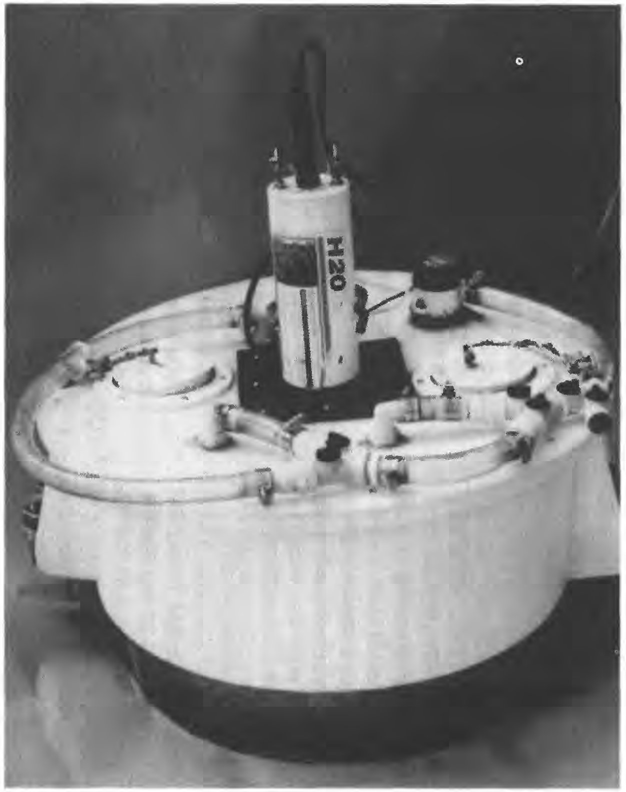



**Figure 2**. Sediment oxygen demand chamber.

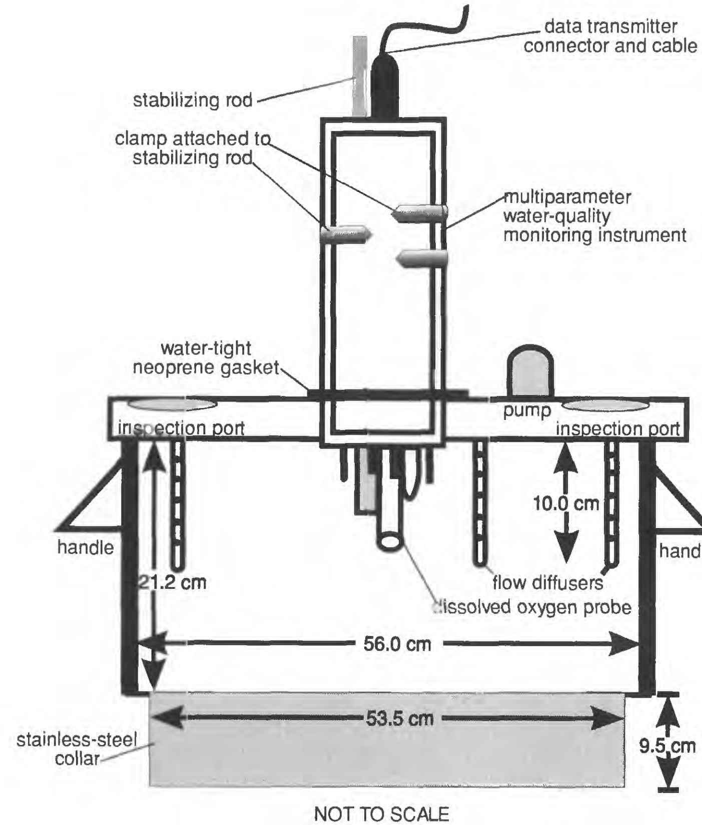



**Figure 3**. Schematic drawing of sediment oxygen demand chamber.

## Deployment and Data Collection Procedures

The steps used to deploy an SOD chamber and monitor the dissolved oxygen loss over time are as follows:

1. A calibrated Hydrolab™ multiparameter probe with a "Lo-Flow" dissolved oxygen membrane is inserted in the chamber and clamped to the stabilizing rod (fig. 3).
2. Near the water surface, the submerged chamber is inspected to check power, pump circulation, and tubing 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 stream. This step is done in preparation for purging the chamber (step 5).
4. With the pump off and inspection ports open, the chamber is lowered and seated in the bottom sediment. For SOD measurements in the main stem Tualatin River, this step is performed by divers. For SOD measurements in the tributaries, an individual wearing chest waders and shoulder length gloves can seat the chamber into the river bed. This step is done with care to minimize disturbance to the bottom sediment. The chamber is left undisturbed for 10 minutes to allow any suspended sediments to settle.
5. After the settling period, the pump is turned on. This purge cycle, with the inspection 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 suspended material, as well as water from the upper part of the water column, is pumped out.
6. After the chamber has been purged for at least 10 minutes (a time period sufficient to flush at least one chamber volume), the ports are closed and the valves are adjusted to recirculate water within the chamber.
7. The starting time and initial readings of DO, pH, water temperature, and specific conductance are noted. The Hydrolab™ is programmed to automatically record probe readings at 5-minute intervals for at least 2 hours. Instrument readings are also recorded manually at 10- to 20-minute intervals.

These seven steps are repeated for each chamber deployed; most SOD measurements were obtained in triplicate at each site. For most of the measurements, a 2-hour time period was used. Some of the data, however, were collected over 5 hours to verify the linearity of the oxygen depletion curve over an extended time period.

## Water-Column Oxygen Demand

In 1992, a closed-bottom chamber of identical dimensions to the open-bottom chamber was used to measure water-column oxygen demand as a "blank" correction. The oxygen depletion rate measured with this closed-bottom chamber was minimal in comparison with that measured in the open-bottom chambers. Half of these measured "blank" corrections (the interquartile range) were between -0.1 and 0.4 $g/m^2d$ with a median of 0.1 $g/m^2d$ (n=17). The median correction was approximately 5 percent of the SOD rate measured with the open-bottom chambers. It is likely, however, that some of the higher "blank" rates were artifacts of oxygen demand from suspended bottom sediment that was accidentally introduced into the "blank" chamber during its placement on the river bottom. Given the relatively low water-column oxygen demand measured with this chamber, and the potential error caused by the accidental introduction of bottom sediments into these chambers, this "blank" correction was not deemed to be large enough, or reliable enough, to continue to measure in subsequent years.

After 1992, a sample of water near the river bottom was collected and the rate of oxygen depletion was measured to determine the magnitude of the water-column oxygen demand over a 2-hour period. Water samples were collected using 300-mL opaque BOD bottles. This near-bottom water sample was placed in a water bath (and located in a shaded area) at river temperature. 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 15- to 20-minute intervals over a 2-hour time period. Water-column oxygen demand measured in this manner was also small (< 3 percent) compared to the SOD measured with the open-bottom SOD chambers. As a result, water-column oxygen demand was discounted as a significant source of oxygen consumption in this procedure.

## Calculation of Sediment Oxygen Demand

The SOD rate is calculated from a graph of dissolved oxygen concentration versus elapsed time. Two hours is usually a sufficient amount of time for a representative oxygen consumption rate to be established in the chambers. Sometimes in the first 10 to 20 minutes of the assay, a rapid and nonlinear decrease in DO concentration is recorded within the chambers (fig. 4). This decrease is thought to be due to a small amount of bottom sediment that had been suspended in the chamber during deployment and had not yet settled back to the sediment surface. Whenever this occurred, the oxygen consumption curve usually stabilized and became linear after the suspended sediment was given

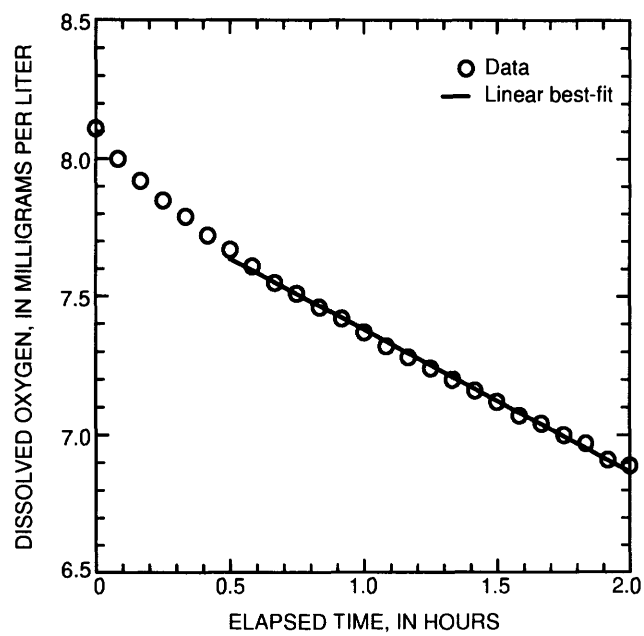



**Figure 4.** Example dissolved oxygen loss curve, showing the typical nonlinear initial loss followed by a linear oxygen loss. (Data taken from a measurement at river mile 5.5 on the main stem Tualatin River on September 9, 1994; this loss curve indicated a sediment oxygen demand of 3.0 grams of oxygen per square meter per day at 20 degrees Celsius.)

time to settle. Only the data obtained after that initial period were used in the calculation of SOD rates. The slope of the linear part of the oxygen depletion line is determined through linear regression, and the following equation is used to calculate the SOD rate:

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

where $SOD_T$ is the sediment oxygen demand rate in $g/m^2d$ at temperature T, b is the slope of the oxygen-depletion curve in milligrams per liter per 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 into the sediments 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°C using a standard van't Hoff equation:

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

where $SOD_{20}$ is the rate at 20°C, and T is in degrees Celsius (°C) (Thomann and Mueller, 1987). This correction does not hold for temperatures less than 10°C; however, temperatures in this study ranged from 14.4 to 23.0°C.

## Statistical Tests

Standard statistical tests were used in the analysis of the SOD rate data, including one-factor and nested analysis of variance (ANOVA), the Mann-Whitney (Wilcoxon) test, and Tukey's multiple comparison test (Helsel and Hirsch, 1992; Box and others, 1978; SAS Institute Inc., 1989; Searle, 1987). Satterthwaite's approximate test procedure (Ostle and Malone, 1988) was used in conjunction with nested ANOVA designs. Rank transformations were used to increase the normality of the data distributions. All tests for statistical significance were made at the 95 percent confidence level.

# FACTORS AFFECTING SEDIMENT OXYGEN DEMAND

All of the SOD rates measured by USGS personnel in the Tualatin River Basin from 1992 through 1996 are shown both in table 1 and figure 5. Ninety-seven rates were measured at nine main-stem sites from 1992 through 1994. Twenty-eight rates were measured at 11 tributary sites from 1995 through 1996. All of the measurements were made during the May through October low-flow period, with a slight emphasis on the month of September, which is a critical period for DO in the main-stem river. During each measurement, the amount of oxygen in the chamber

**Table 1.** Rates of sediment oxygen demand measured in the main stem and selected tributaries of the Tualatin River, Oregon by U.S. Geological Survey personnel, 1992 through 1996

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

| Map number | Site | Date | $SOD_T$ ($g/m^2d$) | Water temperature (°C) | $SOD_{20}$ ($g/m^2d$) |
|---|---|---|---|---|---|
| | **Main stem Tualatin River sites, by river mile (RM)** | | | | |
| 1 | Tualatin River at Stafford Road near Lake Oswego, Oregon (RM 5.5) | 06/17/92 | 3.6 | 18.4 | 4.0 |
| | | | 2.2 | 18.6 | 2.4 |
| | | 10/05/92 | 2.2 | 16.1 | 2.9 |
| | | | 2.9 | 16.1 | 3.7 |
| | | 05/24/93 | 2.8 | 17.2 | 3.4 |
| | | | 3.2 | 17.5 | 3.8 |
| | | | 2.2 | 17.2 | 2.7 |
| | | | 2.8 | 17.5 | 3.3 |
| | | | 2.9 | 17.2 | 3.4 |
| | | | 3.7 | 17.5 | 4.4 |
| | | 09/09/94 | 2.8 | 19.2 | 2.9 |
| | | | 2.3 | 19.2 | 2.4 |
| | | | 2.7 | 19.2 | 2.8 |
| | | | 2.5 | 19.2 | 2.7 |
| | | | 2.9 | 19.2 | 3.0 |
| 2 | Tualatin River at Boones Ferry Road at Tualatin, Oregon (RM 8.7) | 06/15/92 | 1.9 | 18.9 | 2.0 |
| | | | 2.6 | 19.2 | 2.7 |
| | | 08/17/92 | 2.0 | 20.8 | 1.9 |
| | | 10/07/92 | .5 | 15.1 | .6 |
| | | | .5 | 14.8 | .6 |
| 3 | Tualatin River at Cook Park near Tigard, Oregon (RM 10.0) | 05/15/92 | 1.2 | 15.9 | 1.6 |
| | | | 2.1 | 16.4 | 2.6 |
| 4 | Tualatin River near Highway 99W Bridge near King City, Oregon (RM 11.7) | 06/16/92 | 1.9 | 18.3 | 2.1 |
| | | | 2.0 | 18.3 | 2.2 |
| | | 08/20/92 | 2.1 | 21.1 | 2.0 |
| | | | 1.8 | 21.0 | 1.7 |
| | | 05/25/93 | 1.5 | 16.8 | 1.8 |
| | | | 1.9 | 16.8 | 2.3 |
| | | 08/30/93 | 2.4 | 18.7 | 2.6 |
| | | | 1.6 | 18.7 | 1.7 |
| | | | 1.4 | 18.7 | 1.5 |
| | | | 1.9 | 18.4 | 2.1 |
| | | | 1.9 | 18.5 | 2.1 |
| | | 09/08/94 | 3.8 | 18.8 | 4.1 |
| | | | 3.4 | 18.8 | 3.7 |
| | | | 2.2 | 18.8 | 2.4 |
| | | | 2.3 | 18.8 | 2.5 |
| | | | 3.0 | 18.8 | 3.2 |

**Table 1.** Rates of sediment oxygen demand measured in the main stem and selected tributaries of the Tualatin River, Oregon by U.S. Geological Survey personnel, 1992 through 1996—Continued

| Map number | Site | Date | $SOD_T$ ($g/m^2d$) | Water temperature (°C) | $SOD_{20}$ ($g/m^2d$) |
|---|---|---|---|---|---|
| 5 | Tualatin River at Elsner Road near Sherwood, Oregon (RM 16.2) | 06/18/92 | 1.8 | 16.5 | 2.2 |
| | | | 1.9 | 16.6 | 2.8 |
| | | 08/18/92 | 3.2 | 21.2 | 3.0 |
| | | | 2.6 | 21.4 | 2.4 |
| | | 10/06/92 | 1.2 | 14.8 | 1.7 |
| | | | 1.3 | 14.8 | 1.7 |
| 6 | Tualatin River at Lakeside Reclamation near Scholls, Oregon (RM 20.3) | 08/19/92 | 1.8 | 20.9 | 1.7 |
| | | | 1.6 | 20.9 | 1.5 |
| | | 10/08/92 | 2.3 | 14.4 | 3.2 |
| | | | 1.5 | 14.4 | 2.1 |
| | | 05/26/93 | 1.4 | 16.0 | 1.8 |
| | | | 1.2 | 16.0 | 1.5 |
| | | | 2.2 | 16.1 | 2.8 |
| | | | 1.1 | 16.4 | 1.4 |
| | | | 1.8 | 16.5 | 2.2 |
| | | | 1.8 | 16.4 | 2.2 |
| | | 09/03/93 | 1.5 | 18.4 | 1.7 |
| | | | 2.9 | 18.3 | 3.2 |
| | | | 2.1 | 18.3 | 2.3 |
| | | 09/07/94 | 1.6 | 17.7 | 1.8 |
| | | | 2.3 | 17.7 | 2.6 |
| | | | .8 | 17.7 | .9 |
| | | | 1.9 | 17.7 | 2.2 |
| | | | 2.6 | 17.7 | 3.0 |
| | | | 2.5 | 17.7 | 2.9 |
| 7 | Tualatin River at Highway 210 Bridge near Scholls, Oregon (RM 26.9) | 05/27/93 | 2.2 | 16.5 | 2.7 |
| | | | 1.7 | 16.6 | 2.1 |
| | | | 1.8 | 16.6 | 2.3 |
| | | | 2.6 | 16.6 | 3.2 |
| | | | 1.2 | 16.6 | 1.5 |
| | | | 1.5 | 16.7 | 1.9 |
| | | 09/02/93 | 2.6 | 17.7 | 3.0 |
| | | | 2.1 | 18.2 | 2.3 |
| | | | 1.9 | 17.8 | 2.1 |
| | | | 2.2 | 18.2 | 2.4 |
| | | | 1.7 | 18.0 | 1.9 |
| | | 09/15/94 | 1.5 | 16.5 | 1.8 |
| | | | 1.2 | 16.5 | 1.5 |
| | | | 1.4 | 16.5 | 1.8 |
| | | | 1.4 | 16.5 | 1.7 |
| | | | 2.6 | 16.5 | 3.3 |

**Table 1.** Rates of sediment oxygen demand measured in the main stem and selected tributaries of the Tualatin River, Oregon by U.S. Geological Survey personnel, 1992 through 1996—Continued

| Map number | Site | Date | $SOD_T$ ($g/m^2d$) | Water temperature (°C) | $SOD_{20}$ ($g/m^2d$) |
|---|---|---|---|---|---|
| 8 | Tualatin River at Meriwether irrigation pump near Hillsboro, Oregon (RM 36.8) | 08/31/93 | 1.7 | 15.8 | 2.2 |
| | | | 1.1 | 16.5 | 1.4 |
| | | | 1.5 | 15.9 | 1.9 |
| | | | 1.4 | 16.7 | 1.7 |
| | | | 1.2 | 16.1 | 1.5 |
| | | 09/12/94 | 1.3 | 15.8 | 1.8 |
| | | | 2.0 | 15.8 | 2.5 |
| | | | 1.2 | 15.8 | 1.5 |
| 9 | Tualatin River at river mile 43.2 near Hillsboro, Oregon (Jackson Bottom) | 09/01/93 | 1.7 | 15.4 | 2.3 |
| | | | 1.8 | 15.3 | 2.4 |
| | | | 1.6 | 15.8 | 2.0 |
| | | | 1.1 | 15.1 | 1.4 |
| | | | 1.9 | 15.7 | 2.4 |
| | | 09/14/94 | 2.0 | 15.3 | 2.7 |
| | | | 2.2 | 15.3 | 2.9 |
| | | | 1.9 | 15.3 | 2.5 |
| | | | 3.1 | 15.3 | 4.2 |
| | | | 1.8 | 15.3 | 2.4 |
| | **Tualatin River tributary sites** | | | | |
| 10 | Beaverton Creek at Arleda Park near Hillsboro, Oregon | 07/16/96 | 4.9 | 22.6 | 4.1 |
| | | | 5.6 | 22.6 | 4.7 |
| 11 | Bronson Creek at Walker Road at Hillsboro, Oregon | 07/18/96 | 12.7 | 22.4 | 10.9 |
| | | | 4.9 | 22.4 | 4.2 |
| | | | 8.5 | 22.4 | 7.3 |
| 12 | Cedar Mill Creek near Jenkins Road at Beaverton, Oregon | 07/19/96 | 5.4 | 18.0 | 6.1 |
| | | | 2.5 | 18.0 | 2.8 |
| | | | 5.3 | 18.0 | 6.0 |
| 13 | Dairy Creek at Dairy Creek Park at Hillsboro, Oregon | 08/07/95 | 2.7 | 18.0 | 3.1 |
| 14 | Fanno Creek at Durham City Park at Durham, Oregon | 07/15/96 | 1.0 | 23.0 | .9 |
| | | | .3 | 23.0 | .2 |
| 15 | Fanno Creek at Fanno Creek Park at Tigard, Oregon | 08/08/95 | 2.7 | 20.0 | 2.7 |
| 16 | Fanno Creek at Englewood Park at Tigard, Oregon | 07/15/96 | 3.2 | 22.3 | 2.7 |
| | | | 5.1 | 22.3 | 4.4 |
| | | | 5.0 | 22.3 | 4.3 |
| 17 | Gales Creek at Zurcher irrigation pump near Forest Grove, Oregon | 07/19/96 | 7.0 | 16.0 | 9.0 |
| | | | 2.2 | 16.0 | 2.8 |
| | | | 1.9 | 16.0 | 2.5 |
| 18 | Rock Creek near Southeast 59th Avenue at Hillsboro, Oregon | 08/07/95 | 2.1 | 18.0 | 2.4 |
| | | 07/18/96 | 1.9 | 17.5 | 2.2 |
| | | | 2.6 | 17.5 | 3.0 |
| | | | 5.1 | 17.5 | 6.0 |

**Table 1.** Rates of sediment oxygen demand measured in the main stem and selected tributaries of the Tualatin River, Oregon by U.S. Geological Survey personnel, 1992 through 1996—Continued

| Map number | Site | Date | $SOD_T$ ($g/m^2d$) | Water temperature (°C) | $SOD_{20}$ ($g/m^2d$) |
|---|---|---|---|---|---|
| 19 | Rock Creek at Rock Creek Wastewater Treatment Plant at Hillsboro, Oregon | 07/17/96 | 2.8 | 19.4 | 2.9 |
| | | | 4.0 | 19.4 | 4.2 |
| | | | 1.6 | 19.4 | 1.7 |
| 20 | Willow Creek at Apollo Ridge Park at Beaverton, Oregon | 07/16/96 | 1.7 | 19.6 | 1.7 |
| | | | 4.6 | 19.6 | 4.7 |
| | | | 4.3 | 19.6 | 4.4 |

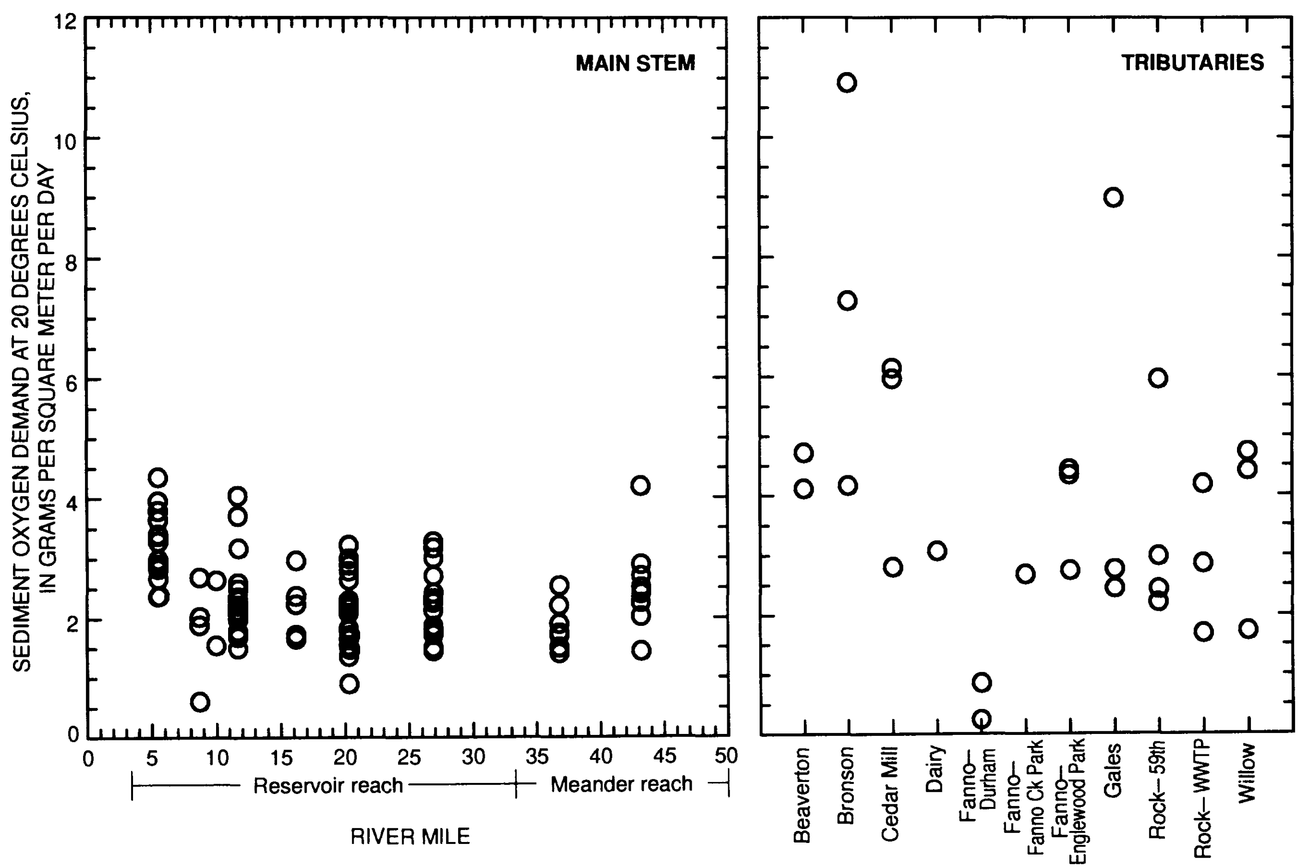



**Figure 5.** Rates of sediment oxygen demand ($SOD_{20}$, corrected to 20 degrees Celsius) measured in the main stem and selected tributaries of the Tualatin River, Oregon by U.S. Geological Survey personnel, 1992 through 1996.

was not a limiting factor. The lowest initial and final DO concentrations encountered were 4.9 and 3.9 mg/L, respectively. Most of the measurements, however, were performed with DO concentrations well above 6.0 mg/L.

The data presented in table 1 and figure 5 were not corrected for water-column oxygen demand, as discussed in the methods section. The BOD measured in the stream water at the sites and times when SOD rates were measured was less than 3 percent of the oxygen loss observed in the SOD chambers. The BOD samples collected in conjunction with these SOD measurements confirmed that a moderate level of BOD does not consume enough oxygen over 2 hours in a volume of 52 liters of water to be important relative to an SOD on the order of 2 $g/m^2d$.

The SOD rate data are highly dependent not only on the ability of the Hydrolab™ to accurately measure oxygen concentration, but also on the volume of water in the chamber and the area of sediment to which that water is exposed. The Hydrolabs™ used proved reliable; pre- and post-calibrations showed minimal instrument drift over a 2- to 5-hour period. Therefore, these instruments were not considered to be a significant source of error in the SOD rates. The area of exposed sediment was determined largely by the size of the chamber. The roughness of the sediment surface introduces some uncertainty into the determination of the effective sediment area, but probably results in an error of no more than a few percent. The volume of isolated water was the least well characterized variable in the calculation of the SOD rate. When the chambers were seated, it was noted whether the "ideal" insertion depth was achieved and, if not, how high or low it was seated relative to that ideal. Volume adjustments were made in the subsequent calculation of the SOD rate (equation 1) on the basis of those observations of insertion depth. Estimates of the actual insertion depth are probably accurate to within one-half inch, resulting in a maximum volume error of about 2.9 liters, or less than 6 percent. On the basis of a maximum volume error of 6 percent and an area error of no more than 3 percent, the total error in these measured SOD rates should be less than 10 percent.

Despite the fact that each individual measurement of SOD is believed to have an error of less than 10 percent, the data in figure 5 indicate that the variability of this rate at any one stream site is much higher than the analytical uncertainty. Coefficients of variation for the rates measured at main-stem sites range from 19 to 31 percent. The variation is probably due to the heterogeneous nature of the bottom sediments; each of the individual measurements was obtained with a different 0.225 $m^2$ of sediment surface. Although the bottom of the Tualatin River from RM 5.5 to 43.2 is predominantly silty and contains a large amount of detrital material and woody debris, simple visual inspection revealed a large amount of variation. Some sedimentary pockets of very fine-grained, almost gelatinous material (the divers described it as "pudding") were observed at most sites. Some of the sediments were characterized by so much silt that the divers had to be careful not to insert the chambers too deeply; other areas were harder and contained more clay. Each site had some of each of these types of sediment.

Overall, the measured SOD rates range from 0.2 to 10.9 $g/m^2d$ with a median of 2.4 $g/m^2d$. Fifty percent of the measurements (the interquartile range) fall between 1.8 and 3.0 $g/m^2d$. These values, especially those from the main-stem Tualatin River sites, are similar to USGS measurements of SOD in 1994 at 15 sites along the lower 50 miles of the Willamette River (1.3 to 4.1 with a median of 2.0 $g/m^2d$, Caldwell and Doyle, 1995). This similarity is not surprising; the sediments of the two rivers are both silty with a moderate content of organic matter (visual determination). Indeed, the range of rates obtained in this study is similar to that obtained for numerous streams with silty sediments elsewhere, excluding those that are heavily impacted by pollution (Murphy and Hicks, 1986; ENSR R&D, 1994; Peter Nolan, U.S. Environmental Protection Agency, personal commun., 1997).

In other waters, the ODEQ found moderate levels of SOD (2.4 $g/m^2d$) in Rickreall Creek near Dallas, Oregon (Larry Caton, ODEQ, personal commun., 1997). ENSR R&D (1994) measured rates of 0.63 $g/m^2d$ in the Chehalis River (Washington), 1.02 $g/m^2d$ in Lake Washington (Seattle, Washington), and roughly 1.9 $g/m^2d$ in the Columbia Slough (Portland, Oregon). Butts (1974) measured rates ranging from 0.56 to 5.0 $g/m^2d$ in the Upper Illinois Waterway. Murphy and Hicks (1986) documented SOD rates at many sites in the southeastern United States and found a range of from 0.5 to 16.6 $g/m^2d$. (All of these SOD rates were corrected to 20°C.) Typically, the lowest rates (0.5–1 $g/m^2d$) are observed for sediments with a high sand component and little organic matter, moderate rates (1–3 $g/m^2d$) are found for silty sediments containing a moderate amount of organic matter, and the highest rates are found at sites polluted with organic sludge from various point sources (Peter

Nolan, U.S. Environmental Protection Agency, personal commun., 1997).

The SOD rates measured in the Tualatin Basin are large enough to be important sinks for dissolved oxygen. In fact, when the BOD is low or the stream is shallow, an SOD of 2 $g/m^2d$ potentially can be the largest sink for dissolved oxygen in the stream. For example, an SOD rate of 2 $g/m^2d$ exerted in a stream with a 3-foot depth, a depth similar to that found in many of the Tualatin's tributaries, will consume more than 2 mg/L of dissolved oxygen in 1 day. For smaller, shallower tributaries, the impact can be even greater. In the reservoir reach of the Tualatin River, where the average depth is typically 10 to 15 feet, an SOD of 2 $g/m^2d$ will consume 0.4 to 0.7 mg/L from the average water-column DO concentration in one day. Because the residence time in this reach is long (up to 14 days), the impact of the SOD can be considerable.

## Stream Order

Beyond the intrinsic variability of the SOD rate at any given site, the data suggest that the rates observed at the tributary sites are higher than the rates observed at the main-stem sites (fig. 6). Figure 6 is a box and whisker plot. In this type of plot, the whiskers extend to the 10th and 90th percentiles of the data, the box extends from the 25th to the 75th percentile, and the median is represented by a horizontal line within the box. Data that fall beyond the range of the whiskers are plotted as individual circles. The median SOD rate for the main stem (n=97) is 2.3 $g/m^2d$, while the median rate for the tributary sites (n=28) is 3.6 $g/m^2d$. A one-factor ANOVA on the original and the rank-transformed data showed that the measured rates from these two groups of sites have statistically different medians at the 95 percent confidence level. A Mann-Whitney test also showed that these two groups were not drawn from the same population.

The reason for this difference is less apparent. Two different hypotheses seem worth further investigation. First, all of the main-stem rates were measured during the 1992 to 1994 period, and most of the tributary rates were measured during 1996 after a major flood in February 1996. The flood might have washed a great deal of fresh, labile organic material from the land into the tributaries (and main stem), causing an inflated SOD rate that will decrease over the coming years as that organic matter ages or is washed farther downstream. The second hypothesis is that the tributaries normally exhibit higher rates of SOD due to their closer interaction with the landscape and their closer proximity to sources of fresh, relatively labile organic matter.

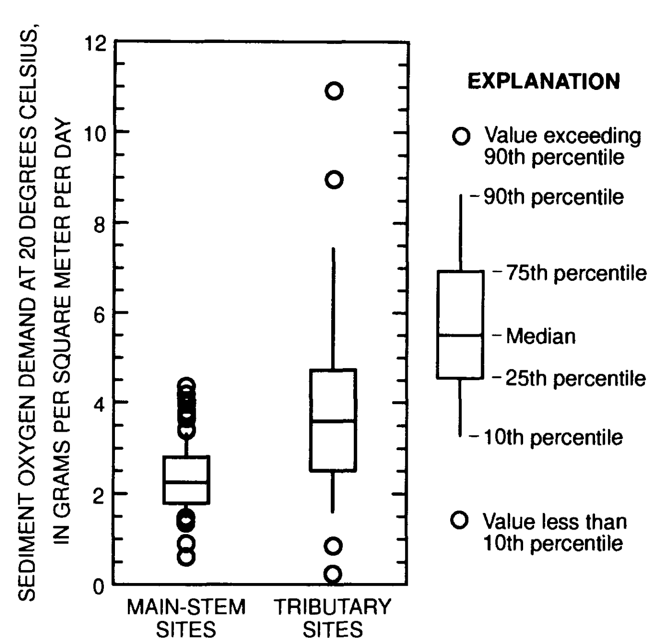



**Figure 6.** Sediment oxygen demand as a function of stream order. (Main-stem sites include 9 sites from river mile 5.5 to 43.2; tributary sites include 11 sites on 8 tributaries.)

This report offers no data to support or refute either of these two hypotheses. Further investigations of SOD rates in both the main stem and the tributaries will help to resolve this issue. However, the fact that (a) the main stem and tributaries are subject to some amount of flooding during each and every winter high-flow season, and (b) particulate organic material that deposits in the main stem probably has aged and become less labile while in transit to that location lends credence to the second hypothesis—the SOD rates exerted in the tributaries normally are higher than those in the main stem.

## River Flow Regime

Within the main stem of the river, the SOD rate does not seem to vary much with location (fig. 5). Measurements were taken in both the meander reach (RM 55.3 to 33.3), and in the reservoir reach (RM 33.3 to 3.4). Both reaches flow slowly enough in the summer to trap sediment, but the reservoir reach in particular is a sedimentary zone that traps a large amount of detrital organic matter. One might expect that the reservoir reach would accumulate more detrital material and therefore exert a higher SOD rate as that material decomposed.

An analysis of the effects of river flow regime (meander reach versus reservoir reach) on the SOD rate must account for other sources of variation, such as any within-site and site-to-site differences. To account for and separate these effects, a nested ANOVA is necessary (Box and others, 1978). This data set does not have an identical number of measurements at each site nor the same number of sites in each flow regime; therefore, this is an unbalanced, nested design. The data were analyzed only for those sites where more than five measured rates were obtained; RMs 8.7 (n=5) and 10.0 (n=2) were left out. Performing an unbalanced, nested ANOVA (SAS Institute Inc., 1989) on the remaining main-stem SOD data produced similar results for both the rank-transformed and the original data. Using Satterthwaite's approximate test procedure on the ANOVA results, no significant differences in the rate data were found due to the two flow regimes (fig. 7).

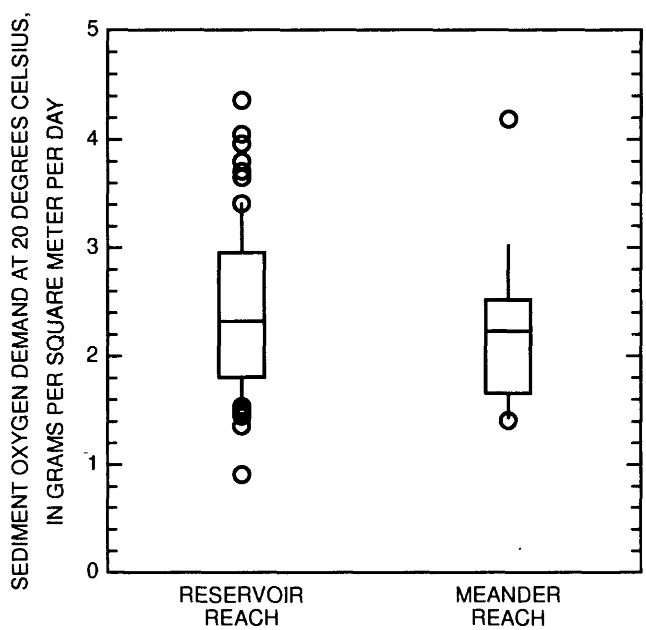



**Figure 7.** Variation in sediment oxygen demand among main-stem sites due to differences in river flow regime. (Reservoir sites include river miles 5.5, 11.7, 16.2, 20.3, and 26.9; meander sites include river miles 36.8 and 43.2.)

By far, most of the differences in the main-stem rate data were due to within-site variability, which accounted for roughly 70 percent of the total variance. Site-to-site differences accounted for the remaining 30 percent of the variance. Tukey's multiple comparison test, using either the original or the rank-transformed data, showed that the SOD rates measured at RM 5.5 (Stafford Road) were significantly higher than those measured at most of the other main-stem sites. The measured rates from the other sites (n>5), however, were not significantly different from one another. These higher rates at RM 5.5 will be discussed in more detail in the next section.

### Phytoplankton

During the low-flow season, the residence time of a water parcel in the reservoir reach of the Tualatin River can be as long as 2 weeks. In conjunction with warm water temperatures, ample solar insolation, and a sufficient nutrient supply, the residence time in this reach is sufficient to produce large blooms (> 50 µg/L chlorophyll-*a*) of phytoplankton. The phytoplankton population generally starts to become significant near the start of the reservoir reach (RM 33.3) and attains fairly high levels by the middle of that reach (about RM 18). The reach from RM 18 to 30 is a transition zone from a "low-concentration" chlorophyll-*a* region upstream of the reservoir reach to a "high-concentration" chlorophyll-*a* reach in the lower part of the reservoir. Figure 8 illustrates this trend in the measured chlorophyll-*a* data for the period over which the main-stem SOD data were collected (May through October 1992–94).

These algal populations produce a large amount of biomass, some of which settles to the bottom of the river and decomposes along with other detrital material. It has been hypothesized that this additional algal detritus, which presumably is relatively labile, would increase the rate of SOD at sites in the "high chlorophyll" zone of the reservoir reach. The rate data collected in this study can be used to test this hypothesis in two ways: spatially and temporally.

With regard to spatial differences, if the phytoplankton die and settle to the river bottom in much the same spatial pattern as the algal population (fig. 8) and if algal detritus increases the SOD rate, then one would expect to find higher SOD rates at sites in the high chlorophyll zone. This hypothesis was tested by grouping the SOD sites according to the three zones in figure 8 and performing a nested ANOVA. Ignoring sites with five or fewer data points, this design groups sites from RMs 5.5, 11.7, and 16.2 in the high chlorophyll zone, RMs 20.3 and 26.9 in the transition zone, and RMs 36.8 and 43.2 in the low chlorophyll zone (fig. 9).

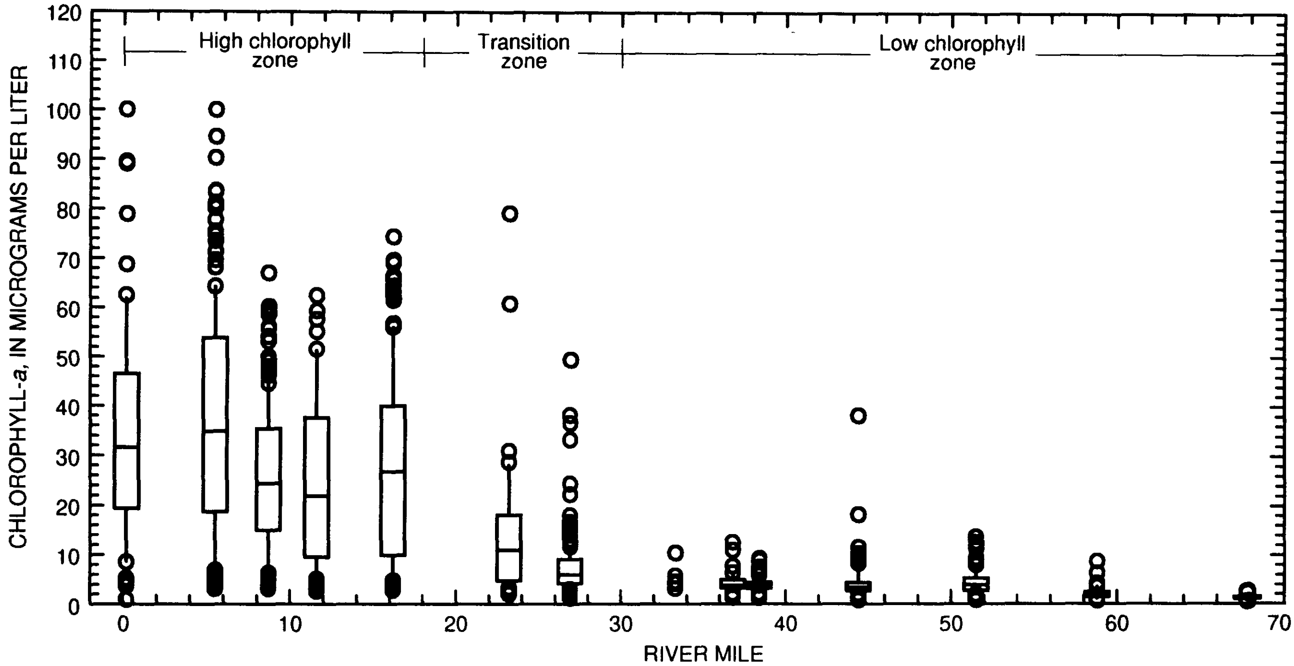



**Figure 8.** Measurements of chlorophyll-*a* at main-stem sites on the Tualatin River during the period May through October of 1992–94. (Data from Unified Sewerage Agency of Washington County; available in STORET.)

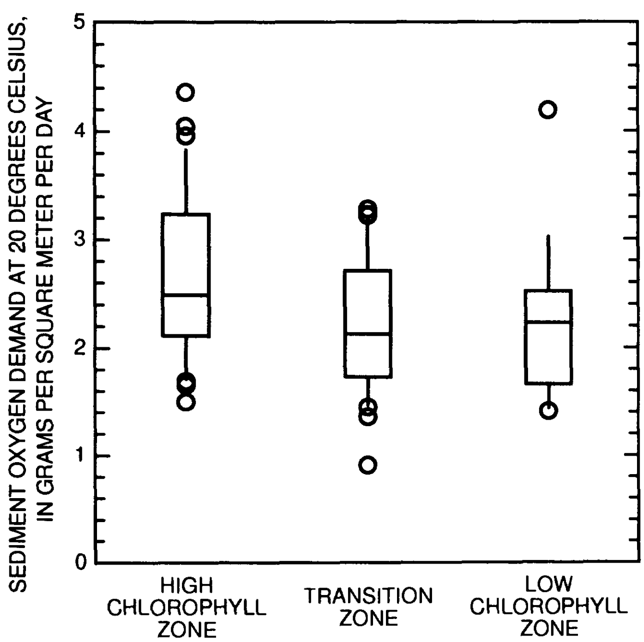



**Figure 9.** Variation in sediment oxygen demand among main-stem sites due to the size of the phytoplankton population. (Sites with high chlorophyll-*a* concentrations include river miles 5.5, 11.7, and 16.2; sites in the chlorophyll-*a* transition zone include river miles 20.3 and 26.9; sites with low chlorophyll-*a* concentrations include river miles 36.8 and 43.2.)

An unbalanced, nested ANOVA was performed on the rank-transformed chlorophyll-*a* data to determine whether the apparent trend in chlorophyll-*a* concentration from one zone to another in figure 8 was statistically significant. Indeed, a significant difference was found among the zones, and Tukey's multiple comparison test resulted in site groups for the three chlorophyll zones that were almost identical to those in figure 8. In contrast, an unbalanced, nested ANOVA performed on either the rank-transformed or the original SOD rate data showed no significant differences between the SOD rates measured in different chlorophyll zones. Instead, the analysis showed that most (70 percent) of the SOD variability was due to within-site heterogeneity and the balance was due to other site-to-site differences.

One site in the high chlorophyll zone, RM 5.5, does have a median SOD rate (3.0 $g/m^2d$) that is significantly higher, by roughly 36 percent, than the median rate for all other main-stem sites (2.2 $g/m^2d$) and all other sites in the high chlorophyll zone (2.2 $g/m^2d$, $n>5$). A one-factor ANOVA and Tukey's multiple comparison test performed on the chlorophyll data only within the high chlorophyll zone shows that the median chlorophyll-*a* concentration at RM 5.5 is significantly higher than at other sites in the high chlorophyll zone where SOD rates were measured (RMs 8.7, 11.7, and 16.2). This result suggests that decomposing algal detritus may contribute to the increased SOD rate at RM 5.5.

Other factors, however, might also be partly responsible for the increased SOD rate at RM 5.5. The bathymetric conditions, for example, might be an important factor. The river is deep (18 feet) at that site, compared with many of the other SOD sites, and is bounded on both the upstream and downstream sides by sills that tend to make this site act as a more efficient depositional area, trapping more detritus than other sites in this reach. Therefore, the bathymetric characteristics of this site may make it unrepresentative of the lowest part of the reservoir reach.

The influence of phytoplankton on the SOD rate can be tested temporally as well as spatially. If the deposition of fresh algal detritus had an effect on the SOD rate, then one would expect the measured SOD rate at a particular site in August or September to be significantly higher than that found at the same site in May or June, before any algal detritus from that season's blooms had been deposited. Four sites on the main stem Tualatin River were used to investigate this potential seasonal dependence. The measured SOD rates at RMs 5.5, 11.7, 20.3, and 26.9 are shown in figure 10, separated according to the time of year. Measurements in May and June were grouped together to represent conditions before any significant algal blooms; generally the first blooms of the year do not occur until mid-June or July, after river discharge decreases to less than 300 $ft^3/s$. Measurements in August, September, and October were grouped to represent conditions after the deposition of fresh algal detritus.

Separate rank-transformed ANOVA and Mann-Whitney tests for each of these four sites revealed no significant seasonal differences in the measured SOD rates at any of these sites (RM 5.5, $p=0.12$; RM 11.7, $p=0.73$; RM 20.3, $p=0.45$; RM 26.9, $p=0.80$). Any small effect of the deposition of fresh algal detritus, if present, is masked by the intrinsic heterogeneity of the SOD rate at each site.

This result, and that from the spatial analysis, indicate that algal detritus is not a primary source of organic matter for the SOD. The decomposition of algal detritus may contribute to the SOD at some locations, but most of the SOD is likely to originate from nonalgal sources of organic matter.

## SUMMARY AND CONCLUSIONS

SOD was measured using in-situ benthic chambers at 20 sites on the main stem and tributaries of the Tualatin River during the low-flow summer periods of 1992 through 1996. Measured water-column BOD was too small to interfere with these measurements of

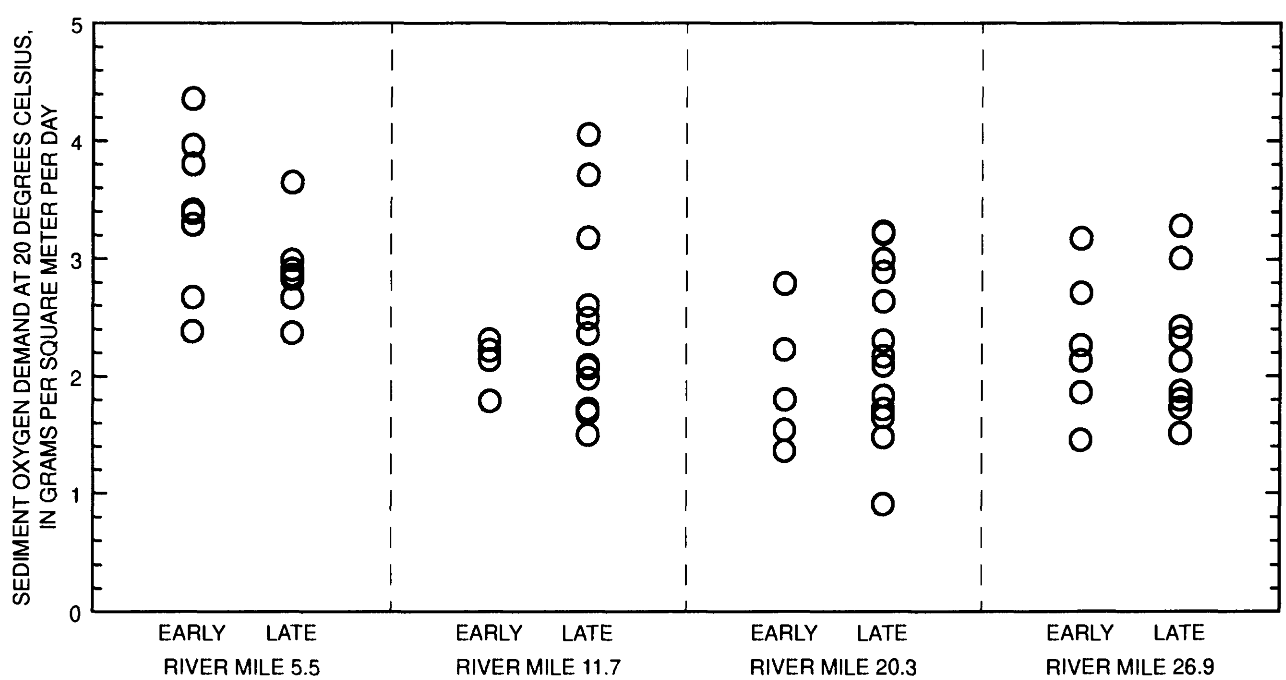



**Figure 10.** Seasonal variations in sediment oxygen demand at four main-stem sites. (Early indicates measurements made in May and June; late indicates measurements made in August, September, and October.)

SOD. Measurement error was estimated to be less than 10 percent, and bed-sediment heterogeneities at any one site led to variations in the SOD rate that were much larger than the estimated measurement error. For the main-stem sites, within-site heterogeneities accounted for 70 percent of the variation in the SOD rate, while small site-to-site differences accounted for the balance of the variation. The measured SOD is large enough to be a major sink for oxygen in the Tualatin River and its tributaries.

Generally, the SOD rates measured at the tributary sites (median of 3.6 $g/m^2d$, n=28) were found to be significantly higher than those measured at the main-stem sites (median of 2.3 $g/m^2d$, n=97). This difference may have been due to the closer interaction of the tributary sites with the surrounding landscape and their proximity to sources of fresh, labile organic matter, or it may be an artifact of the large flood of February 1996. Within the main stem, no differences due to the effects of the river flow regime (meander versus reservoir reach) were found among the sites. Furthermore, the temperature-corrected SOD rate was not correlated with zones of high chlorophyll-*a* concentration, and no significant temporal effects were found. Although the decomposition of algal detritus may contribute to an increased SOD rate at one site (RM 5.5), algal detritus was not found to be a primary influence on the measured SOD rate. Because the effect of algal detritus was mostly undetectable with these data, a large majority of the SOD is likely to originate with nonalgal inputs of organic matter.

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