Effect of Flow Velocity on Sediment Oxygen Demand: Experimental Results

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Heinz G. Stefan

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Environmental Research Laboratory
Duluth, Minnesota 55804

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ABSTRACT

Sedimentary oxygen demand, SOD, frequently the major oxygen consumer in lakes, is the uptake of dissolved oxygen, DO, by sediments. The oxygen is removed from the water column by chemical oxidation processes and by the respiration of microbes in the sediments. To effectively counteract oxygen depletion especially in lakes, an improved understanding of SOD is required. In 1994 Nakamura and Stefan published a theory relating SOD to flow velocity using boundary layer concepts. This paper is an experimental validation and extension of those results. In this study SOD is investigated in laboratory experiments in which sediments are exposed to water flowing at different velocities. The experiments were performed in a recirculating channel with well defined flow characteristics. The results verify that SOD increases with the velocity of the water above the sediments. However, this velocity effect is found to have an upper bound. The rate of increase with velocity as well as the upper bound of SOD are shown to depend on the sediment material, the benthic biology, and the temperature. SOD is approximated by linear and Michaelis-Menten type equations with velocity being the independent variable.
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1. INTRODUCTION

In 1994 Nakamura and Stefan published a theory relating SOD to flow velocity using boundary layer concepts. This paper is an experimental validation and extension of those results.

The biochemical decomposition of organic materials in lake sediments makes a major, if not the largest demand on dissolved oxygen in winterkill lakes (Ellis and Stefan, 1989), i.e. ice-covered lakes with little inflow and outflow, in which fish die for lack of oxygen. Dissolved oxygen depletion is also observed in the hypolimnion of thermally stratified eutrophic lakes during the summer. In these lakes the rate of downward dispersion of dissolved oxygen from reaeration and photosynthesis of the surface layers is not high enough to compensate for sedimentary oxygen uptake. The release of nutrients including phosphorus and of some heavy metals are secondary undesirable effects of dissolved oxygen depletion near the sediments (Mortimer, 1971, Chapra and Canale, 1991; Furnmai and Ohgaki, 1989).

Sedimentary oxygen demand (SOD) can be determined in several fundamentally different ways, each with its own advantages and disadvantages. In one method, SOD is determined as the residual of a hypolimnetic (summer) or total (winter) dissolved oxygen, DO, budget of a lake. The rate of net loss (or gain) of DO from the lake water can be determined from measurements of DO concentrations over depth at several times throughout the period of interest. DO sources and sinks other than SOD need to be measured or estimated and subtracted from the net oxygen loss rate of a lake to determine the SOD. These sources and sinks may include biochemical oxygen demand (BOD) of detritus particles in the water column, photosynthesis and respiration of plants and animals in the hypolimnion (summer) or under the ice (winter), and dispersive transport from above. A second method of determining SOD rates uses dome like chambers placed on the lake sediments with a collar penetrating into the lake sediments. The DO in the water volume isolated in the dome is measured repeatedly and from its decrease the SOD is calculated. A discussion of methods to measure SOD is given in other literature, e.g. by Cerco et al. (1992).

Typical SOD values are from 0.5 g m$^{-2}$ d$^{-1}$ for sandy bottoms to 10 g m$^{-2}$ d$^{-1}$ for very organic sediments. Values above 20 g m$^{-2}$ d$^{-1}$ are found in very productive tropical water (Veenstra and Nolen, 1991). There is considerable indirect evidence that water velocities, even small ones, have a strong effect on SOD. The evidence is fourfold.

(1) It has often been observed that artificial aeration devices, e.g. air bubble plumes, designed to compensate for SOD values measured in stagnant water, fail to fulfill expectations. It is postulated that these installations increase the water circulation in the lake and hence SOD, indicating that these devices are underdesigned.
(2) SOD values measured in chambers increase considerably with necessary and appropriate mixing inside the chamber, but what is "appropriate" has not been quantified (Cerco et al., 1992).

(3) There exist some measurements which show an increase of SOD with flow rate (Belanger, 1981; Boynton et al., 1981). Increases of SOD by an order of magnitude have been reported at velocities below 10 cm/s (Cerco et al. 1992). Increases in SOD start at very low velocities that occur naturally in lakes.

(4) One can show theoretically, using mass transfer through laminar and turbulent boundary layers, that SOD should increase with flow velocity over the sediments (Nakamura and Stefan, 1994).

Current numerical lake water quality models, which include SOD, describe chemical and biological kinetics at the sediment/water interface by zero or first order kinetics (e.g. DiToro et al., 1990) but do not recognize or include the velocity dependent diffusive flow through the water boundary layer, although it can be the rate limiting process. Bacteria in the sediments and the chemical decay of plant and animal matter, draw dissolved oxygen (DO) out of the overlying water. In calm water a steep gradient in the DO concentrations can be set up above the sediment (Figure 1). Very low currents can disturb this boundary layer and cause a substantial increase in the rate of SOD.

The goal of the study described herein was to measure the effect of water velocity on sediment oxygen demand (SOD) under well-controlled conditions in large scale laboratory experiments. An experimental confirmation or disagreement with theoretical relationships (Nakamura and Stefan, 1994) was sought. This goal was accomplished by circulating a fixed volume of water (2.83 m³) over a sediment bed of 3.72 m² surface area. The water boundary layers at different flow rates were characterized by velocity profile, boundary layer thickness, and shear velocity. This is a more precise documentation than in previous investigations. Experiments with sediments of different properties were conducted. The sediments were characterized by organic material content, total organic carbon, and density. The rate of dissolved oxygen depletion was measured at different water circulation rates. Relationships between SOD (g m⁻²d⁻¹) and flow velocity (cm/s) above the bed were obtained for each sediment studied.
Figure 1. Schematic distribution of (a) dissolved oxygen concentration and (b) flow velocity. The boundary layer is divided into a viscous sublayer and the turbulent layer (After Nakamura & Stefan, 1993).
2. EXPERIMENTAL EQUIPMENT AND PROCEDURES

2.1 Concept of the Experimental Flow Facility

A recirculating channel in which flow velocities could be controlled was required for these experiments. Velocities from 0 to 30 cm/s (0-1 ft/s) were needed to represent lake bottom conditions. A recirculating channel was required because a hydraulic (water) residence time of several hours was necessary to assure a measurable drop in the bulk oxygen concentration. To simulate natural conditions in lakes, the boundary layer of the flow in the experimental channel had to be fully developed while passing over the sediment. A sufficient length of channel was therefore required before the sediment bed to allow for redevelopment of the boundary layer on each pass through the channel. The SOD was calculated by the bulk oxygen method. Sealing the channel from air eliminates reaeration from the atmosphere. Photosynthesis was virtually impossible because the experiments were conducted in a dark environment. Calculation of the SOD during an experiment was then quite simple because DO sources had been eliminated, and the only DO sinks were SOD and the consumption of DO in the water itself which was measured separately as BOD.

Cumulative DO consumption by the sediment bed is calculated by subtracting the DO concentration in the channel from the measured DO concentration in the BOD samples at each sampling time. The slope of the line produced by plotting the cumulative DO consumption over time is then calculated. This slope is the SOD and is converted to standard units (gm⁻²d⁻¹) by multiplying it by the volume of water in the channel and dividing by the area of the sediment surface, i.e.

\[
\text{SOD} = \left( \frac{[\text{DO}]_{\text{BOD}} - [\text{DO}]_{\text{channel}}}{\Delta t} \right) \cdot \frac{V_w}{A_s}
\]

where

- \([\text{DO}]_{\text{Channel}}\) = DO concentration in the channel (mgL⁻¹)
- \([\text{DO}]_{\text{BOD}}\) = DO concentration in the BOD samples (mgL⁻¹)
- \(\Delta t\) = Duration of time from beginning of experiment to sampling time
- \(\theta_{\text{Regression}}\) = Slope of the regression analysis
- \(V_w\) = water volume in the flume = 2.83 m³ = 100 ft³
- \(A_s\) = surface area of sediments = 3.7 m² = 40 ft²

2.2 Design, Construction, & Characterization of the Experimental Flow Facility

A 15 m (50 ft) long laboratory channel, 0.60 m (24 inches) wide and 0.40 m (16 inches) high, was rebuilt for the experiments. A divider wall was placed horizontally
near mid-depth in the channel to let the water recirculate above the divider. The divider and false bottom were constructed of galvanized steel to minimize corrosion. Figure 2 is a sketch of the channel.

A pump in a by-pass loop was provided to add momentum to the flow in order to balance friction forces in the channel. The bypass flow withdrew and reinjected about 37% of the total flow. Intake and discharge manifolds were placed in the upper-return duct just after the water returned from the bottom to maximize the distance from the multiport jets to the sediment bed, in order to maximize dissipation of turbulent jet energy. To facilitate the resetting of different flow rates, flow meters were installed in the bypass line. Although these meters did not measure the total flow in the channel, they could be used to reset known flow rates in the channel after calibration.

Head loss constraints led to the selection of a 0.175 m (7 inch) height for the flow over the sediment bed and a 0.125 m (5 inch) height for the return flow. To avoid flow separation, turning vanes were installed at both channel ends, and honeycombs were installed downstream from the vanes for further flow straightening and turbulent energy dissipation. Another concern was to prevent oxygen transfer from the air. A one inch thick styrofoam top cover was therefore cut to fit in the channel without gaps. A sediment depth of 0.05 m (2 inches) was chosen for the experiment. SOD is generally independent of depth of sediment for sediment depths greater than 0.02 to 0.08 m (Owens et al., 1964 and Fillos and Molof, 1972).

Design flow Reynolds numbers based on water at room temperature (20°C) and a hydraulic diameter for the duct equal to \( D_h = \frac{4A}{P} = 0.276 \text{ m} \), indicated that the flow would be laminar (\( \text{Re} < 2400 \)) at mean flow velocities below approximately 0.01 m/s and turbulent above that value. The velocity profile in turbulent pipe flow can be considered fully developed in 50 diameters conservatively, or 20 diameters effectively. The distance from the turning vanes at the upstream end of the duct to the beginning of the sediment layer is 7.5 m (25 ft) or approximately 28 hydraulic diameters, hence sufficient to develop the velocity profile fully in turbulent flow (Figure 3). Laminar flow takes a longer distance to develop, but even then, the laminar velocity profile was anticipated to be well developed at the entrance to the test section with the sediment bottom.

Velocity profiles were measured to determine the average velocity, maximum velocity, boundary layer thickness and average shear stress (shear velocity) on the bed. Turbulent velocity profiles were measured with an electro-magnetic Marsh-McBirnie model 523 current meter (EMCM). When the EMCM was used, the digital data acquisition permitted numerical averaging over appropriate sampling periods. Measurement of laminar velocity profiles required the timed photography of dye streaks in the channel since these velocities are too slow for the EMCM. Potassium permanganate and 5,5,7-Indigotrisulfonic acid crystals were the dyes used for this purpose. Velocity measurements obtained by the dye tracing method were repeated up to six times for averaging. Velocity profiles at six different flow rates
Figure 2. Side View of the Experimental Channel, 15m (50ft) long, 0.61m (2') wide
Figure 3. Schematic of Boundary Layer Growth and Velocity Profile in the Channel
were measured. The electromagnetic current meter was used to measure four of the profiles and the photographic technique was used for the measurement of the other two profiles.

All vertical profiles were plotted in Cartesian coordinates and on semi-log graphs before further analysis. Semi-log plots are appropriate for calculating shear velocity for the turbulent velocity profiles which follow the relationship

\[
\frac{u(y)}{u_*} = \frac{1}{\kappa} \ln y + C
\]

where \(u(y)\) = velocity at distance \(y\)
\(u_*\) = shear velocity = \(\sqrt{\tau_b/\rho}\)
\(\tau_b\) = bottom shear
\(\rho\) = density of water
\(\kappa\) = 0.41 = von Karman constant
\(C\) = constant of integration

The slope of the semi-log plot, \(u_*/\kappa\), was determined by linear regression from all measured velocity profiles. A separate \(u_*\) was first calculated for each vertical profile and then a weighted average \(V_*\) was calculated for the total channel width (using the width for which each profile was representative as a weight factor).

\[
V_* = \frac{\sum u_{*i} b_i}{\sum b_i}
\]

Newton's shear law was applied to laminar velocity profiles at 0.10 and 0.30 m (4 and 12 in.) from the channel wall to calculate the bed shear stress, \(\tau_b\), at the low flow rates.

\[
\tau_b = \mu \left( \frac{du}{dy} \right)_b
\]

where \(\mu\) = water viscosity (N*sec/m²)
\(\left( \frac{du}{dy} \right)_b\) = slope of laminar flow velocity profile at the bottom

The regression was forced through \(u=0\) at \(y=0\). \(V_*\) for laminar flows is then determined using the equation \(\tau_b = \rho V_*^2\).

Maximum velocities \(u_c\) were also taken from each profile at elevation \(y = H/2 = 0.089\) m or the nearest measurement point (usually \(y = 0.076\) or \(0.102\) m). A width-weighted average \(V_*\) was calculated for each flow rate similar to the weighted
average shear velocity (equ. 3). A total volumetric flow rate Q was calculated by integrating velocity profiles over the areas i.e. integrating first over height and then over width. An average flow velocity was then found by dividing Q by the cross-sectional area of the channel (0.108 m² = 1.17 ft²). All values are listed in Table 1. The average velocity and average maximum velocity were plotted over pump flow rate and the plots were linear. This was expected because the manifold jet velocity is proportional to pump flow rate and flow entrainment velocity is proportional to jet velocity (Mackenthun and Stefan, 1994). It was decided that the six flow rates tested adequately characterize the experimental channel and that velocity conditions at other flow rates could be obtained by interpolation between measurements.

<table>
<thead>
<tr>
<th>Pump Flow Rate (gpm)</th>
<th>6</th>
<th>10</th>
<th>25</th>
<th>35</th>
<th>45</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Flow Rate, Q (m³/s)</td>
<td>0.000778</td>
<td>0.00150</td>
<td>0.00415</td>
<td>0.00599</td>
<td>0.00797</td>
<td>0.0109</td>
</tr>
<tr>
<td>Avg. Velocity, Vavg (cm/s)</td>
<td>0.72</td>
<td>1.39</td>
<td>3.83</td>
<td>5.52</td>
<td>7.35</td>
<td>10.02</td>
</tr>
<tr>
<td>Max. Centerline Vel., Vc (cm/s)</td>
<td>0.88</td>
<td>1.58</td>
<td>4.70</td>
<td>6.39</td>
<td>8.80</td>
<td>11.92</td>
</tr>
<tr>
<td>Shear Velocity, V* (cm/s)</td>
<td>0.075</td>
<td>0.123</td>
<td>0.289</td>
<td>0.340</td>
<td>0.647</td>
<td>0.633</td>
</tr>
<tr>
<td>Shear stress, (Pa)</td>
<td>0.000559</td>
<td>0.00151</td>
<td>0.00832</td>
<td>0.0115</td>
<td>0.0418</td>
<td>0.0401</td>
</tr>
</tbody>
</table>

Flow velocities were kept low enough so that there was no visual resuspension of sediments.

2.3 Design and Construction of Barrel Experiments

Barrel experiments were constructed and used primarily to determine a temperature relationship for SOD in temperature controlled rooms which were much smaller than the experimental channel. The barrel consists of a half filled 55 gallon steel drum with a floating cover on the water surface. Synchronous interchangeable electric motors control the rate of rotation of the cover. The motor is mounted on top of the barrel and drives a square shaft that fits through a slot in the cover. The shaft ends in a small cup fixed on the center of the barrel bottom. An outlet is placed 0.18 m (7 in.) from the bottom of the barrel and is controlled by a valve. The outlet is used for the collection of samples.

Sediment is placed 5 m (2 in.) deep in the barrel and water covers the sediment to a depth of 0.30 m (12 in.). Motors run at speeds of 1 or 4 rpm. This results in maximum cover velocities between 0.03 and 0.12 m/sec at the periphery of the cover.
2.4 Determination of Sediment Characteristics

Sawdust was chosen as the first sediment because it is a fairly well defined organic material with an expected high rate of SOD. This was desirable because the greatest sensitivity to velocity was expected from sediments with high rates of SOD. Other purely organic materials were considered for use as sediments including cracked corn and haylage, but these spoiled too quickly.

Following the study with sawdust, experiments with actual lake sediment were conducted. The sediment was taken from among the reeds surrounding the open water to insure high organic content. One batch of sediment was taken out of Diamond Lake in Minneapolis, Minnesota, the other was from Tiger Lake near Norwood, Minnesota.

Several sediment properties were measured to characterize the sediments including bulk density, density of dry solids, percent organic matter and percent total carbon (Table 2). As expected the sawdust was less dense and had a higher organic matter and total carbon content than did the other sediments. Interestingly, the organic matter content of the Tiger Lake sediment was 46% higher than the organic matter content of the Diamond Lake sediment while the total carbon content of the Diamond Lake sediment was 29% higher than the total carbon content of the Tiger Lake sediment.

<table>
<thead>
<tr>
<th>Table 2. Sediment Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Matter</td>
</tr>
<tr>
<td>(%)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Sawdust</td>
</tr>
<tr>
<td>Diamond Lk Sed.</td>
</tr>
<tr>
<td>Tiger Lake Sed.</td>
</tr>
</tbody>
</table>

2.5 Dissolved Oxygen and BOD Measurements

Dissolved oxygen was measured in water samples by the Winkler titration method. Water samples of 300 ml were taken from the channel. Dissolved oxygen measurements were made with two or three replicas every time. The standard error of the D.O. measurements was less than 0.02 mg/l. Standard Methods (APHA, 1992) gives a precision of 0.05 mg/l for an experienced analyst using visual end-point detection.
The BOD of the water was measured in samples taken at the beginning of each experiment. These samples were also collected in 300 ml BOD bottles. As water samples were taken to measure the DO level in the main channel, the BOD could be measured from the samples collected earlier.

2.6 Experimental Procedures

Sediment was placed into the test section with the water drawn down until it just covered the false bottom. The sediment was graded with a board to smooth the surface. The channel was slowly filled with water and reassembled. Before the experiment could be started the D.O. concentration in the water had to be raised to near saturation. Aeration was provided by two dome shaped porous stone aerators placed on the bottom of one end of the channel. The channel water was circulated continually to ensure a uniform distribution of oxygen and aerobic conditions. Time was allowed for the sediment to settle and stabilize before an experiment.

When an experiment was to begin the aeration source was disconnected, the pump was set to the desired flow rate, and the top of the channel was sealed. At least half an hour was allowed for the flow to reach a quasi-steady state. The water temperature was measured and water samples were taken in 300 ml BOD bottles. The bottles were kept near the channel so that their temperature was maintained near the temperature of the channel. Six to eight water samples were taken initially for BOD measurements so that replica BOD measurements could be made several times throughout the experiment. Each experiment was allowed to run for about 24 hours. Figure 4 illustrates that the DO of the channel water dropped linearly with time, in other words, that the rates of BOD and SOD seemed to be constant over the duration of each experiment. Steady-state conditions for flow and oxygen uptake were desired.

The DO level in the channel usually dropped one to two mg/L during an experiment, and when a run was completed, aeration was again begun to ensure that the channel never became anaerobic before the next experiment. Reaeration from the atmosphere was made impossible by the cover on the experimental flume. Even if there had been minute contact between air and water, the near saturation DO concentration of the channel water would make reaeration rates extremely small. Water was added to the channel occasionally to replace water that was lost to samples. Tap water was used for the experiments with sawdust as sediment, river water was used during the experiments with Diamond Lake and Tiger Lake sediments.

Before the sawdust was placed in the channel, it was soaked in tap water until it was saturated. A small amount of river water was added for inoculation of the sawdust with microorganisms. After soaking for about 10 days it was placed in the channel and tap water was added. Testing was begun about 10 days later to allow time for the sawdust to stabilize. The Tiger Lake and Diamond Lake sediment were
both placed in the channel within one week of their collection, and were allowed to settle for several days before the first experiment.

The barrel experiments were conducted in four temperature controlled rooms with temperatures ranging from 3 to 28 °C. The barrel was left in the appropriate room for at least one day prior to the first experiment to allow the temperature in the barrel to reach near equilibrium with the room.
Figure 4. Example of the Linear Rate of Sediment Oxygen Utilization, 3rd Sawdust Experiment on, 45 gpm Pump Flow Rate
3. EXPERIMENTAL RESULTS

3.1 Temperature Dependence of SOD

SOD is a temperature dependent process. Temperature dependence was determined in the barrel experiments using Tiger Lake sediment. Table 3 contains the data which are also plotted in Figure 5. Data were taken with two different motor speeds driving the cover. This explains the vertical offset of the two data sets in Figure 5.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Day from Motor Speed (rpm)</th>
<th>Max. Motor Vel. of Water (cm/s)</th>
<th>Water Temp. (°C)</th>
<th>SOD (gO₂/m²/d)</th>
<th>BOD (mg/L d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>4</td>
<td>11.90</td>
<td>17.8</td>
<td>1.160</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>4</td>
<td>11.90</td>
<td>16.9</td>
<td>1.049</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>4</td>
<td>11.90</td>
<td>27.2</td>
<td>1.535</td>
</tr>
<tr>
<td>4</td>
<td>19</td>
<td>4</td>
<td>11.90</td>
<td>6.7</td>
<td>0.731</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
<td>4</td>
<td>11.90</td>
<td>3.5</td>
<td>0.514</td>
</tr>
<tr>
<td>6</td>
<td>33</td>
<td>1</td>
<td>2.98</td>
<td>26.5</td>
<td>1.215</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>1</td>
<td>2.98</td>
<td>21</td>
<td>1.017</td>
</tr>
<tr>
<td>8</td>
<td>42</td>
<td>1</td>
<td>2.98</td>
<td>9.5</td>
<td>0.512</td>
</tr>
<tr>
<td>9</td>
<td>52</td>
<td>1</td>
<td>2.98</td>
<td>4.3</td>
<td>0.365</td>
</tr>
</tbody>
</table>

Two methods of adjusting kinetic rates to a standard temperature of 20°C are popular. One is the Arrhenius equation and the other is a simple linear correction. The data were analyzed for each and both yielded good results. The linear regression was slightly better, and had an average $R^2$ value of 0.99. The resulting linear correction equation is

$$SOD(20°C) = SOD_T + 0.0404 (20 - T) \quad (5)$$

The Arrhenius equation is used in the simplified form

$$SOD(20°C) = SOD(T) \ 6^{(20-T)} \quad (6)$$
Figure 5. SOD Data from Barrel Temperature Dependence, Experiments 1-5 using a 4 rpm motor, Experiments 6-9 using a 1 rpm motor.
Rewriting the equation in logarithmic form

\[
\ln\left(\frac{\text{SOD}(20^\circ\text{C})}{\text{SOD}(T)}\right) = (20 - T)\ln(\theta)
\]

allows the computation of \(\theta\) as the slope of the plot of \(\ln(\text{SOD}(20^\circ\text{C})/\text{SOD}(T))\) against \((20 - T)\). Figure 6 shows this plot. The analysis yielded a temperature correction coefficient \(\theta = 1.05\), which is near the lower end of values reported by Zison et al. (1978) and close to the expected average value of 1.065 derived from a literature review (Thomann and Mueller, 1987). The regression for this calculation had an \(R^2\) value of 0.95.

3.2 Velocity Dependence of SOD

3.2.1 Sawdust Experiments

BOD depends on oxidizable materials in suspension or in solution in the recirculated water. Therefore material leaching or resuspended from the sediments is important. BOD values are plotted against the age of the channel water in Figure 7. Initially high, the BOD values decreased over time. The causes are believed to be the gradual depletion of oxidizable soluble and suspendable materials in the water.

Figure 8 shows SOD plotted over time. Measured SOD rates are summarized in Appendix III for all experiments. A trend of decreasing values of SOD with time is apparent and is explained by the changing microbiology.

SOD is plotted against average velocity in Figures 9 a, b, c, and d. An increase in SOD with flow velocity is readily apparent and confirms the theory by Nakamura and Stefan (1994) for low flow velocities. There is also a significant change in SOD rates over time. It was therefore appropriate to divide the SOD data into several sets as shown in Figure 9:

Set 1: Experiments 1 to 4 were conducted with fresh sediment. This set was completed within 4 days of the beginning of the experiments. The sediment had been submerged in water for at least 19 days prior to the start of the experiments.

Set 2: Experiments 5 to 11 were started 6 days after the end of Set 1 and were completed 19 days later. Over this more extended period, some transformations in the properties of the sediment appear to have occurred. SOD results are scattered.

Set 3: Experiments 12 to 20 began 31 days after experiment 1 and lasted 23 days. Microbes in the form of clusters and mats which had first appeared during Set 2 were much in evidence.
Figure 6. Temperature Dependence SOD Data Plotted for Calculation of theta
Figure 7. BOD vs. Time from Sawdust Experiments
Figure 8. SOD vs. Time from Sawdust Experiments
Figure 9(a) SOD vs. Average Velocity, Set 1, Sawdust Experiments

Figure 9(b) SOD vs. Average Velocity, Set 2, Sawdust Experiments
Figure 9(c) SOD vs. Average Velocity, Set 3, Sawdust Experiments

Figure 9(d) SOD vs. Average Velocity, Set 4, Sawdust Experiments
Set 4: Experiments 21 to 29 began after an extended inactive period of about 80 days. A continuous microbiological mat up to 5 mm thick had formed and remained in place.

Plots of SOD against shear velocity, $V_s$, or maximum velocity, $V_{\text{max}}$, are also meaningful and can be produced using the linear velocity conversions given in Table 1 and expressed as

$$V_s = 0.0659 \ V_{\text{avg}} + 0.0344 \quad \text{(cm/s)} \quad (8)$$

$$V_{\text{max}} = 1.19 \ V_{\text{avg}} \quad (9)$$

Approximately one month after the sawdust was placed in the channel i.e. during the course of experiments of set 2, microbiological growth colonies began appearing on the surface of the sediment bed. These were believed to be fungi. Soon the water in the channel became quite cloudy while it had previously been clear. Thereafter a biofilm was forming on the glass walls of the channel. It lasted approximately two weeks and was followed by a natural clearing of the channel water. Subsequently, only the microbiological growth remained on the sediment bed as a thick mat. The growth of the biological mat coincided with a strong decrease in SOD. It is apparent that the biological mat acted as a barrier retarding DO transfer to the sediments. SOD became dependant to a greater extent on diffusion of DO through the biological mat rather than diffusion though the laminar boundary layer.

Over time a horizon developed in the sediment about one centimeter below the surface; it was visible through the glass wall of the channel. The deeper sediment became a darker brown while the top one centimeter remained a light brown to yellow color. This was interpreted as an indication that the deeper sediment had become anoxic.

3.2.2 Diamond Lake Sediment Experiments

BOD values are listed against age of the channel water in Figure 10. No definite trends can be identified though it appears that BOD values increase rapidly from 0.1 mg/l d before leveling off around 0.4 mg/l d. BOD accounted in the average for less than 10 % of the DO loss during an experiment. SOD is plotted over time in Figure 11.

SOD over average velocity is plotted in Figure 12 a,b, and c. Some interdependence between flow velocity and SOD is apparent, but unlike the sawdust experiments an upper limit for SOD is clearly reached in the last two experimental sets. Again the data show an evolution in time. It was therefore again appropriate to divide the SOD data into sets:
Figure 10. BOD vs. Time from Diamond Lake Sediment Experiments
Figure 11. SOD vs. Time from Diamond Lake Sediment Experiments
Figure 12(a) SOD vs. Average Velocity, Set 2, Diamond Lake Sediments
Figure 12(b) SOD vs. Average Velocity, Set 3, Diamond Lake Sediments
Figure 12(c)  SOD vs. Average Velocity, Set 4, Diamond Lake Sediments
Set 1: Experiments 1 and 2 were after the sediment had been submerged in river water for about 90 days. This set is not plotted.

Set 2: Experiments 3 to 6 were started two weeks after the end of Set 1 and were completed one week later. The data (Figure 12a) yield a fairly linear trend of SOD increase with velocity through a velocity of about 4 cm/s.

Set 3: Experiments 7 to 14 began 36 days after set 2 ended. The SOD at each velocity is higher than it was during set 2. At a velocity of about 3 cm/s, the SOD rate levels off at 0.8 g O$_2$/m$^2$ d.

Set 4: Experiments 15 to 21 followed set 3 by two weeks. The data points are slightly more scattered than the other data sets. There is also a trend of increasing SOD rate with velocity to approximately 3 cm/s after which the rate levels off near 0.85 g O$_2$/m$^2$ d.

The Diamond Lake Sediments were left in the aerated channel for 90 days before the experiments were started. During that time several interesting observations were made and some oxidation of the sediments occurred. This may explain the low measured values of SOD.

During the first few days that the Diamond Lake sediment was in the channel the sediment expanded and the average depth of sediment in the test section swelled from five to nine centimeters. A few days later, gas production in the sediment caused the release of bubbles from the sediments. The gas was either carbon dioxide or methane. Though there were no windows in the building and little direct light on the sediment, plants sprouted from the sediment for the first few weeks. They were pulled, the trapped gas was released by lancing the bubbled areas, and the sediment was regraded. Soon after the sediment was placed in the channel leeches 3 to 7 cm long were observed in the channel water. Also leeches were seen protruding from the sediment with their bodies waving back and forth in the current. The leeches were trapped and removed from the channel until they were observed only infrequently. Over time the water in the channel became clearer. About two months after the placement of the sediments, two horizons of different color became visible through the glass walls in the channel. About 1.3 cm below the surface of the sediment, the sediment became very dark and the glass became stained light orange. Again this was interpreted as an indication that the deeper sediment had become anoxic.

As with the sawdust, the dependance of SOD on velocity was reduced during the course of the experiments. Also, over time, the highest rate of SOD seemed to be reached at lower velocities. Both observations may be explained by the fact that SOD rates become less dependant on velocity if the upper layer of sediment is depleted of organics thereby increasing the importance of DO diffusion through the sediments rather than the water.
3.2.3 Tiger Lake Sediment Experiments

BOD values are listed against age of the channel water in Figure 13. No trends can be identified. BOD accounted for only 11% of the DO loss during an average run. SOD over time is plotted in Figure 14. SOD is plotted in Figures 15 a and b over average velocity. It was again appropriate to divide the SOD data into sets:

Set 1: Experiments 1 to 9 began after the sediment had been submerged in river water for about 60 days and were completed 19 days later. The data are scattered, but appear to follow the pattern of the experiments with Diamond Lake sediments where the SOD increases gradually with velocities before nearing an upper limit. The upper limit appears near 2.8 g O₂/m² d, significantly higher than the limit of the Diamond Lake sediment.

Set 2: Experiments 10 to 15 were started one day after the end of Set 1 and were completed three weeks later. The SOD increases rapidly at low velocities, but does not display the expected upper limit. The SOD rates reach 4 g O₂/m² d.

Diamond Lake and Tiger Lake sediments behaved similarly in some ways and differently in others. One difference was the lack of clarity of the channel water. Instead of clearing up fairly rapidly, it became quite dark and remained that way for 4.5 months during the Tiger Lake sediment experiments. During this time a film developed on the channel walls. After 4.5 months the water cleared up and the film on the glass wall dissipated.

When the Tiger Lake sediment was placed in the channel no animals were observed at first. About a month after the sediment was placed in the channel thousands of tubifex appeared projecting out of the sediment and waving back and forth in the current. These tubifex were less than a centimeter long. By the end of the experiments they seemed to be dead but they were still visible. Towards the end of the experiments worms were observed burrowing through the sediment along the glass channel walls. They were about 2.5 cm long and less than 1 mm in diameter. Tunnels were observable through the sediment along the glass walls at times.

During the course of the first set of experiments, SOD increased with velocity and an upper limit of SOD near 2.8 mg/m² d was apparent. The second set of experiments showed SOD increasing more rapidly with velocity than the first set with no apparent upper limit. The only explanation for this disparity is the biological activity observed. The tubifex protruding above the sediment would disturb the boundary layer and increase SOD. The burrowing of tunnels into the sediment is also likely to increase the exchange of water and the rate of SOD. The effect of velocity on SOD would be magnified by a network of miniature tunnels in the sediments.
Figure 13. BOD vs. Time from Tiger Lake Sediment Experiments
Figure 14. SOD vs. Time from Tiger Lake Sediment Experiments
Figure 15(a) SOD vs. Average Velocity, Set 1, Tiger Lake Sediments
Figure 15(b) SOD vs. Average Velocity, Set 2, Tiger Lake Sediments
4. ASSESSMENT OF RESULTS

During the course of this study changes were observed in the appearance of the sediment and the variety of organisms in the channel. Microbiological and macrobiological communities were not considered quantitatively, but undoubtedly had an effect on the results. This is considered important because in most SOD studies it is usually assumed that the benthos will be stable over time.

Diamond Lake and Tiger Lake are similar types of lakes. Both are shallow hypereutrophic lakes. Tiger Lake is larger and is in a rural area while Diamond Lake is in a suburban area. It was expected that the sediments would behave similarly in the laboratory experiments. This was not the case for either the biological observations or the measured SOD rates.

In all sets of experiments SOD increases with velocity increases as long as velocities are low. In some cases the velocity dependence ceased when the average velocity reached 3 cm/s, in others the velocity dependence continued beyond 10 cm/s average velocity. Typically the velocity dependence begins as a linear relationship near zero velocity. The sawdust experiments yielded linear increases throughout the range of velocities tested. This implies that the SOD was limited by DO diffusion through the water boundary layer above the sediment. The experiments with Diamond Lake Sediments showed linear increases in SOD only at the lowest velocities. This implies the SOD was limited by DO diffusion through the water boundary layer above the sediments at low velocities, but at higher velocities SOD became dependent on the rate of DO use and diffusion in the sediment.

Following this study SOD models for lakes, ponds and similar "standing waters" should contain a dependence on velocity and an upper SOD limit. Estimating the upper limit as a function of sediment quality should be the goal of further research. The value of the upper limit is undoubtedly related to the rates of chemical oxidation, microbiological oxygen consumption, and diffusion in the sediments (Nakamura and Stefan, 1994). If there is a dominance of chemical SOD in the deeper sediments resulting from anaerobic oxidation of organics, the rate of SOD is limited by the diffusion of DO through the pores of the aerobic layer of sediment, not by the rate of diffusion through the water boundary layer above the sediment.

The equation below can be used to fit curves through the linear portion of the data. The values of \( \text{SOD}_0 \) and \( m \) for each set of data are presented in Table 4. This is simply a linear equation with an upper limit beyond which the velocity dependence ends.

\[
\text{SOD} = \text{SOD}_0 + m \text{V}_{\text{avg}} \quad \text{SOD} < \text{SOD}_{\text{max}}
\]
where $SOD_o$ = SOD at zero velocity (g m² d⁻¹)
$SOD_{max}$ = SOD beyond which SOD is independent of velocity.

In this relationship $V_{avg}$ is used, but it must be noted that $V_s$ (shear velocity) may be more meaningful to express the SOD vs. flow velocity relationship, because the mass transfer from the water to the sediment will be hindered most severely by the viscous sublayer above the sediment. The thickness of that layer will be inversely proportional to shear velocity. In the experiments shear velocity and average velocity are related as shown in Table 1.

The data can also be fitted to a Michaelis-Menten type equation of the form

$$\frac{SOD - SOD_o}{SOD_{max} - SOD_o} = \frac{V_{avg}}{K + V_{avg}}$$

(11)

where $K$ is the kinetic rate constant. This equation incorporates the upper bound, $SOD_{max}$ and is a continuous function. By equating the initial slopes of equations (10) and (11), one can obtain the relationship

$$K = \frac{SOD_{max} - SOD_o}{2m}$$

(12)

Parameter values for $K$ are given in Table 4.

<p>| Table 4. Coefficients for SOD Velocity Dependence Models |
|-----------------|--------|-----------------|--------|--------|--------|</p>
<table>
<thead>
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<th>SODo</th>
<th>m</th>
<th>SODmax</th>
<th>k (cm/s)</th>
</tr>
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<td>$(g \text{ O}_2/\text{m}^2 \text{ d})$</td>
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In a natural environment, e.g. a lake or bay, the parameters \( SOD_o \), \( SOD_{\text{max}} \), and \( m \) can be determined if velocities are measured at the same time as \( SOD \). The data in Table 4 indicate values for two lake sediments: \( SOD_o \) from 1.0 to 0.6 g \( \text{O}_2 \) m\(^{-2}\)d\(^{-1}\), \( m \) from 0.15 to 1.7 g \( \text{O}_2 \) m\(^{-2}\)d\(^{-1}\) cm\(^{-1}\)s\(^{-1}\), \( SOD_{\text{max}} \) from 0.8 to larger than 3.7 g \( \text{O}_2 \) m\(^{-2}\)d\(^{-1}\). In the few experiments conducted with lake sediments over periods of several weeks, \( SOD_o \) values increased, \( m \) values decreased, and \( SOD_{\text{max}} \) values increased or decreased over time, as biological changes took place. This may be fortuitous and needs further experimentation.

Figure 16 is a schematic of the types of \( SOD \) responses to velocity changes that we would expect in a variety of aquatic environments. The experimental results compare favorably to the theory by Nakamura and Stefan (1993). The shapes of the \( SOD \) vs. velocity functions are the same. One can therefore conclude that the oxygen transfer through the water boundary layer has been correctly analyzed and accounted for in the theory. The parameters \( SOD_o \), \( m \) or \( K \), and \( SOD_{\text{max}} \) can be related to the parameters in the kinetics used by Nakamura and Stefan, but we shall not attempt this here. Instead we shall briefly examine how the parameters \( SOD_o \), \( m \) or \( K \), and \( SOD_{\text{max}} \) can be related to other measurable/observable physical, microbiological, macrobiological, and chemical parameters of the sediments: \( SOD_{\text{max}} \) is the DO uptake rate when mass transfer through the water boundary layer (velocity effect) imposes no limit. \( SOD_{\text{max}} \) must therefore depend on sediment characteristics, micro- and macro-biological populations and efficiencies, surface chemistry and diffusion through the sediments. Here we have measured only a few sediment parameters (Table 2). A correlation of \( SOD_{\text{max}} \) with OM(%) or TC(%) can be expected. The data in Figures 17 and 18 are sparse, but show a potential relationship: \( SOD_{\text{max}} \) goes up as OM and TC increase.

On the other end of the scale, when water velocities are zero i.e. \( SOD = SOD_o \), transfer through the water boundary layer to the sediment surface becomes crucial. It has already been remarked that \( SOD_o \) values go up with time. This is indicative of more efficient DO transfer to the sediments at zero water velocity. This may be, however, related to biofilm growth or macroorganisms (tubifex). The biofilm may become the oxygen consuming layer, rather than the sediments. This is speculative and other interpretations may be possible. A relationship between \( SOD_o \) and sediment properties such as OM or TC should not be expected. Indeed average values of \( SOD_o \) are more or less independent of OM and TC at about 0.4 g \( \text{O}_2 \) m\(^{-2}\)d\(^{-1}\). The variation around this average is however very large (0 to 1.1 g \( \text{O}_2 \) m\(^{-2}\)d\(^{-1}\)) due to biological variability. Zison et al. also reported SOD values unrelated to total organic carbon (TOC) content of the sediments.

Not surprisingly no relationship was found between the value of \( m \) in equation 10 and sediment parameters, since \( m \) is linked to all elements of the system: water boundary layer, biofilm, microbial kinetics in the sediments, diffusion in the sediments and chemistry. What is required is a reliable method of classifying sediments with respect to both the physical/chemical makeup of the sediment and the biological environment.
Figure 16. Schematic of the Types of SOD/Velocity Response Curves Found.
Figure 17. SOD$_{\text{max}}$ vs. Organic Matter

- ▲ Sawdust
- ● Diamond Lake Sediment
- ■ Tiger Lake Sediment

Figure 17. SOD$_{\text{max}}$ vs. Organic Matter
Figure 18. SOD$_{\text{max}}$ vs. Total Carbon
5. SUMMARY AND CONCLUSIONS

(1) This experimental study has shown that the sedimentary oxygen demand (SOD) can significantly increase with water velocity. This indicates that D.O. transfer through the water boundary layer (viscous sublayer) can control the SOD. SOD also has an upper bound at which an increase in water velocity does not increase SOD any longer. This confirms a previously developed theory by Nakamura and Stefan (1994).

(2) Experimentally determined SOD has also shown a strong dependence on benthic biological conditions. Microbial mats can reduce the maximum SOD and dependence of SOD on velocity, while leeches and tubifex can increase SOD by creating tunnels in the sediment or by disturbing the viscous sublayer which increase the rate of transport of DO into the sediments.

(3) The rate of increase of SOD with water velocity and the upper bound are controlled by the nature of the sediments and the micro and macrobiology. The upper bound is specifically controlled by the organic material content and the rate of oxygen diffusion through sediment pores to deep sediments. For sediments from Diamond Lake the upper bound was found to be about 1 g m$^{-2}$ d$^{-1}$; for Tiger Lake it was higher than 2.8 g m$^{-2}$ d$^{-1}$.

(4) Further experimentation is required to relate the SOD at zero velocity ($\text{SOD}_0$), the rate of increase of SOD with velocity, $m$, and the upper limit of SOD, $\text{SOD}_{\text{max}}$, to sediment properties and benthic biology.

(5) When estimating SOD one should characterize a water body taking into consideration flow velocity and sediment characteristics such as organic matter content, macrobiological populations and activity, and microbiological layers.

(6) For DO modeling, this experimental study suggests that the "system" which controls SOD is a multiple layer system. Going from above to below the oxygen flux encounters

(1) a turbulent water boundary layer
(2) a viscous sublayer
(3) a surface microbial and macrobiological layer
(4) a sedimentary oxic layer
(5) a sedimentary anoxic layer.
SOD is then controlled by the transfer rates (diffusion coefficients) through these five layers and the oxygen uptake rates (kinetic rate coefficients) in the microbial surface layer (three) and the sediments oxic layer (four).

Macro-organisms (e.g. leeches, tubifex) cause disturbances in the viscous sublayer (two) and the sedimentary oxic layer (four) which result in increased vertical diffusion by mixing (water) or channeling (sediments). Near bottom flow velocities control the transfer through the turbulent water boundary layer including the viscous sublayer.
REFERENCES


APPENDICES
## Appendix I. Results of All SOD Velocity Dependence Experiments

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<th>Avg. Slope (mg/l min)</th>
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<th>Corr. SOD Temp. (g O2/m² d)</th>
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(Continued)
## Appendix I: Results of All SOD Velocity Dependence Experiments (continued)

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A = area (m²);
BOD = biological oxygen demand, loss of DO in the water column (g/L d);
\( D_h \) = hydraulic diameter = \( 4 \ast \frac{A}{P} \) (m);
DO = dissolved oxygen concentration (mg/L);
DOC = dissolved organic carbon (% of dry weight);
P = Perimeter (m);
PFR = pump flow rate (gpm);
Q = volumetric flow rate (m³/s);
\( Re_x \) = Reynolds number, \( V_x \ast u \), a measure of flow turbulence;
SOD = Sediment Oxygen Demand, flux of \( O_2 \) to sediment (g \( O_2 \) m²d⁻¹);
TOC = total organic carbon (% of dry weight);
\( u(y) \) = velocity at distance \( y \) from the bottom of the channel (m/s);
\( u_* \) = shear velocity at the point of measurement (m/s);
x = distance from the end of the channel (m);
\( V_{av} \) = Average velocity (m/s);
\( V_e \) = 1 maximum velocity, 2 width weighted average maximum velocity (m/s);
\( V_* = \sqrt{\frac{\tau_b}{\rho}} \), width weighted average shear velocity (m/s);
\( \delta \) = fully developed boundary layer thickness (m);
\( \theta \) = Arrhenius equation temperature correction coefficient (-);
\( \kappa \) = 0.41, von Karman constant;
\( \mu \) = water viscosity (Nsec/m²);
\( \tau_b \) = bed shear stress (Nm²);
\( \nu \) = kinematic viscosity (m/s);
\( \forall_w \) = total water volume (m³);
Bibliography


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