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FACTORS AFFECTING SEDIMENT OXYGEN DEMAND DYNAMICS IN BLACKWATER STREAMS OF GEORGIA'S COASTAL PLAIN[1]

Barbra C. Utley, George Vellidis, Richard Lowrance, and Matt C. Smith[2]

ABSTRACT: Sediment oxygen demand (SOD) is believed to be an important process affecting dissolved oxygen (DO) concentrations in blackwater streams of the southeastern coastal plain. Because very few data on SOD are available, it is common for modelers to take SOD values from the literature for use with DO models. In this study, SOD was measured in seven blackwater streams of the Suwannee River Basin within the Georgia coastal plain for between August 2004 and April 2005. SOD was measured using four *in situ* chambers and was found to vary on average between 0.1 and 2.3 g O_2/m/day across the seven study sites throughout the study period. SOD was found to vary significantly between the watersheds within the Suwannee River Basin. However, land use was not found to be the driving force behind SOD values. Statistical analyses did find significant interaction between land use and watersheds suggesting that an intrinsically different factor in each of the watersheds may be affecting SOD and the low DO concentrations. Further research is needed to identify the factors driving SOD dynamics in the blackwater streams of Georgia's coastal plain. Results from this study will be used by the Georgia Department of Natural Resources – Environmental Protection Division as model input data for the development and evaluation of DO total maximum daily loads in the Georgia coastal plain.

(KEY TERMS: sediment oxygen demand; dissolved oxygen; coastal plain; Georgia; blackwater streams; watersheds; water quality.)

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INTRODUCTION

The tributaries of the main blackwater river systems (Ochlockonee, Satilla, St. Mary's, and Suwannee) in Georgia's coastal plain (Figure 1) regularly violate Georgia Department of Natural Resources – Environmental Protection Division (Georgia EPD) dissolved oxygen (DO) standards. The blackwater rivers and streams, named for the black color of their deep water, are tinted by organic acids leached from the swamps on the tributary floodplains (Meyer, 1990; Dosskey and Bertsch, 1994; Meyer *et al.*, 1997). These river systems are also characterized by low topographic gradients and from late spring to late autumn, by high temperatures and low flows. They are also

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[2]Respectively, Doctoral Candidate, Biological Systems Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061; Professor, Biological and Agricultural Engineering Department, University of Georgia, Tifton, Georgia 31793-0748; Ecologist, USDA-ARS Southeast Watershed Research Laboratory, Tifton, Georgia 31793; and Research Leader, USDA-ARS Animal Manure and By-Products Laboratory, ANRI, Beltsville, Maryland 20705 (E-Mail/Vellidis: yiorgos@uga.edu).

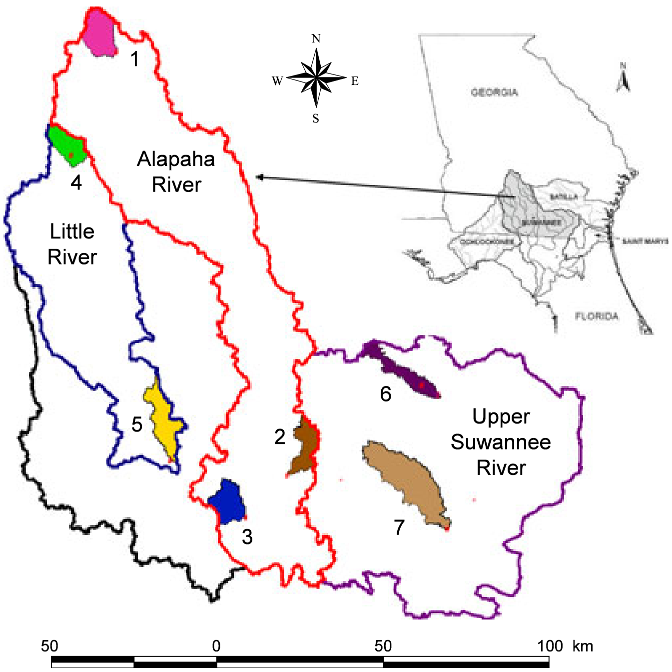

FIGURE 1. Map Showing the Location of the Study Sites Within the Suwannee River Basin. Watershed 1 is an agricultural study site while Watersheds 2 and 3 are forested study sites within the Alapaha River 8-digit HUC. Watershed 4 is the agricultural site and Watershed 5 is the forested site within the Little River HUC. Watersheds 6 and 7 are the forested study sites within the Upper Suwannee River HUC.

characterized by low DO concentrations and low concentrations of suspended sediments (Meyer, 1990).

In many regions of the United States (U.S.), low DO is a common freshwater impairment. Clearly, low DO is not a pollutant. However, it is commonly presumed that DO concentrations below the standard are associated with increased biological activity resulting from N (nitrogen) and P (phosphorus) enrichment. This increased biological activity is generally excessive algal growth. When excessive algal blooms decay, DO is depleted due to the biochemical oxygen demand (BOD) of the decomposition process. BOD exerts an oxygen demand in the water column and contributes to biotic and abiotic oxygen demand in the sediments (Lee, 2003). As the organic matter decays, aerobic bacteria deplete the available oxygen within the lower water column at a faster rate than oxygen diffusion from surface waters (Rabalais, 2002). Therefore, hypoxic conditions will remain if oxygen consumption rates are greater than oxygen resupply.

All States, Territories, and Tribes of the U.S. are required to regularly assess water bodies within their jurisdictions and develop total maximum daily loads (TMDLs) for waters not meeting established water quality standards, including DO, in accordance with Section 303(d) of the Clean Water Act and the US Environmental Protection Agency Water Quality Planning and Management Regulations (40 CFR Part 130). During 2003, 91% of all coastal plain streams considered impaired in Georgia violated DO standards. These streams were placed on the Georgia 303(d) list.

However, recent research in Georgia and Louisiana indicates that low DO may be a natural condition for summer months in coastal plain streams (Bosch *et al.*, 2002; Ice and Sugden, 2003; Vellidis *et al.*, 2003). Without a good understanding of the ecological processes governing DO dynamics in coastal plain streams, it is not possible to address the cause of low DO. One of the key ecological processes affecting DO concentrations is sediment oxygen demand (SOD), also known as benthic oxygen demand.

Sediment Oxygen Demand

Sediment oxygen demand is the rate at which DO is removed from the overlying water column by biochemical processes in the stream bed sediments (Hatcher, 1980). The sediments that make up the benthic zone of the stream originate from natural stream conditions, nonpoint source runoff, and wastewater effluents (Hatcher, 1980; Matlock *et al.*, 2003). Significant rates of sediment oxygen uptake have been observed in rivers and estuaries that do not receive large amounts of solids from point sources. SOD rates observed under these natural conditions are due to soluble organic substances in the water column, which are derived from naturally occurring sediments containing aquatic plants and animals as well as detritus discharged into the water body from natural runoff (Truax *et al.*, 1995).

Several factors affect SOD rate. Primary focus is often given to the biological components such as organic content of the benthic sediment and microbial concentrations. Three of the most important parameters affecting SOD, as described in the literature, are temperature near the sediment-water interface, stream depth (Ziadat and Berdanier, 2004), and the overlying water velocity (Truax *et al.*, 1995). Specifically, SOD increases linearly with velocity at low velocities (<10 cm/s) but becomes independent at high velocities (Makenthun and Stefan, 1998). Ziadat and Berdanier (2004) found that depth was the most important hydrologic variable effecting SOD in Rapid Creek, South Dakota. The base SOD rate changes throughout the year due to multiple factors including: DO concentration in the water column, seasonal benthic population changes, mixing rate of the overlying water, presence of toxic chemicals, and changes in temperature.

Sediment oxygen demand values can be measured through laboratory or *in situ* methods, both of which are expensive but may produce accurate rate measurements (Hatcher, 1980). *In situ* techniques have been found to be more accurate in general than laboratory respirometers (Whittemore, 1986). *In situ* chambers measure either the drop in DO concentration over time (batch method) or the difference in DO concentration in the inflow and outflow (continuous method) (Lee *et al.*, 2000).

The most common method for measuring SOD is the utilization of a batch reactor that encloses a given amount of sediment with a known volume of water and measures oxygen depletion over time (Truax *et al.*, 1995). Measuring SOD in the field requires controlling or understanding many alternate variables. For example, increasing the sediment surface area allows for the integration of microhabitat patchiness, while decreasing the height of the chamber allows for greater sensitivity to low metabolic rates (Boynton *et al.*, 1981).

Also, a sufficient water column should be present over the sediment to allow the re-establishment of steady state conditions (Truax *et al.*, 1995). A schematic of an *in situ* chamber deployed in a stream channel is shown in Figure 2. Once the oxygen depletion data are collected over a given retention time, the SOD rate is calculated based on the area of sediment enclosed, the volume of water contained in the chamber, and the rate of oxygen uptake (Whittemore, 1986).

In general, field measurements minimize the manipulation of the sediment and more accurately reflect ambient conditions than do laboratory methods.

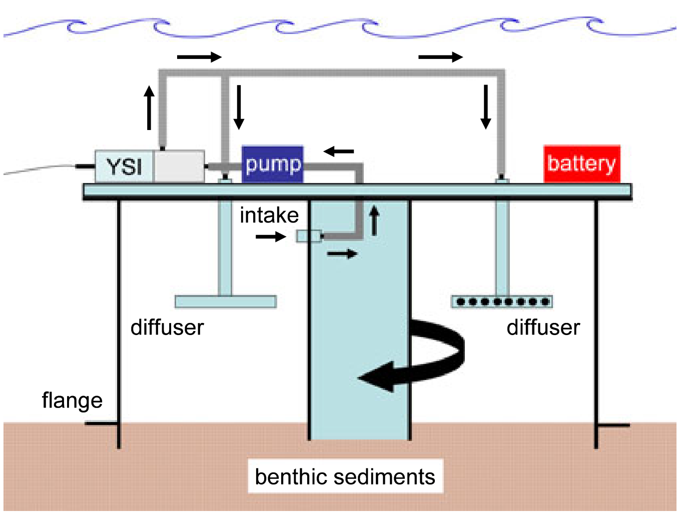

FIGURE 2. Schematic of a Deployed SOD Chamber. Diffusers on either side of the chamber promote water circulation through the annular shape of the chamber.

However, field measurements are conducted under more dynamic ambient conditions that impact the accuracy of the tests. Also, field measurements do not guarantee undisturbed sediments as it is very difficult not to disturb sediments while deploying the chambers whether this is done via diving or wading into the stream. Currently, there is not a universally accepted method for measuring SOD in the field making comparisons of data difficult (Chau, 2002).

Research conducted on streams has found that benthic organic carbon is inversely proportional to the mean annual stream temperature, and benthic respiration is directly proportional to temperature (Sinsabaugh, 1997). Maximum respiration rates, for a blackwater stream in southern Georgia, have been recorded during the summer and early autumn, while the minimums were measured during winter and early spring (Meyer *et al.*, 1997). There was no statistically significant correlation between measured SOD and sediment characteristics in the Williamette River in Oregon (Caldwell and Doyle, 1995). Hill *et al.* (2002) measured benthic microbial respiration of 0.40 ± 0.05 g O_2/m^2/day in coastal plain streams and 0.40 ± 0.06 g O_2/m^2/day in piedmont steams. SOD values measured in stream systems vary greatly (Table 1), and the variability can be enhanced by point source pollution. For example, Truax *et al.* (1995) reported values from 0.1 to 33 g O_2/m^2/day have been measured downstream from paper mills in the southeastern U.S. As seen in Table 1, there is a large range of SOD values measured in the U.S. The values in the literature vary based on location and a combination of physical parameters. However for a specific type of stream and sediment combination, for example blackwater streams with sandy beds, very few data are available.

Extensive environmental monitoring is difficult and expensive; therefore, mathematical modeling is frequently used to simulate natural systems and make regulatory decisions. DO models require many parameters including temperature, depth, velocity, BOD, chemical oxygen demand, and SOD (Chaudhury *et al.*, 1997; Vellidis *et al.*, 2006). Models that do not

TABLE 1. Reported SOD Values in the United States.

Region	SOD ($gO_2/m^2/d$)	Reference
Eastern U.S.	0.15 ± 0.04	Truax *et al.*, 1995
South Eastern U.S.	0.55 ± 0.22	Truax *et al.*, 1995
Oregon	1.3-4.1	Caldwell and Doyle, 1995
Arkansas	0.15-1.36	Matlock *et al.*, 2003
Missouri	1.2-2.0	Borsuk *et al.*, 2001
South Dakota*	3.80-6.98	Ziadat and Berdanier, 2004

Notes: SOD, sediment oxygen demand.
*A control chamber was not used in this study to remove water column respiration from the SOD.

adequately predict SOD can seriously misrepresent the DO dynamics within the stream. For example, Matlock *et al.* (2003) found SOD to be responsible for 50% of the total oxygen depletion within the stream adding weight to the idea that SOD is one of the most important parameters within a DO model. A modeling study conducted on the Little River Experimental Watershed (LREW) in Georgia's coastal plain (as a companion to this study) found that estimating SOD as the remaining oxygen demand in the model, assuming all other parameters were known and measured correctly, can seriously misrepresent the true SOD being exerted on they system (Cathey, 2005; Cathey *et al.*, 2005).

Objectives

This study is part of an on going project to determine the natural range of DO concentrations in Georgia's coastal plain streams. Our objective was to obtain a better understanding of SOD dynamics in blackwater streams draining a range of different land use types from relatively undisturbed forest/wetland watersheds to highly disturbed agricultural sites. We hypothesized that SOD rates would vary across different land uses. For example, we expected that forested watersheds would have higher SOD rates than agricultural watersheds due to higher rates of allochthonous organic matter.

MATERIALS AND METHODS

Site Selection

Within Georgia, the Suwannee River Basin contains four 8-digit HUCs (United States Geological Survey Hydrologic Unit Code): the Withlocoochee, Little, Alapaha, and Upper Suwannee (Figure 1). Twenty potential study sites were identified within these HUCs. Of these twenty, seven sites were selected for the study based on the procedures described below. Three sites were located within the Alapaha River HUC, two within the Little River HUC, and two within the Upper Suwannee River HUC (Figure 1). Two of the seven study sites were selected to be in watersheds where 50% or more of the land use is agriculture. The other five study sites were selected to be in watersheds that have greater than 50% forested land use.

Land use was determined at the 12-digit HUC scale using ARCView® (ESRI, Redlands, CA) and 1998 land use data collected by the Georgia Department of Natural Resources. Potential watersheds between 3000 and 7000 ha were delineated using AV-SWAT 2000 extension (Blackland Research Center, Texas A&M University, Temple, TX) for ARCView® GIS. Watersheds of this size were chosen so that streams would be perennial while main river channels would be avoided. Streams of this size are accessible throughout the year except directly after a storm event. Twenty potential watersheds were identified from this first selection. The outlet of these watersheds was then identified as a potential SOD site for SOD measurements. Each potential site was visited and evaluated based on its suitability for SOD measurements. Suitability was determined by accessibility to the stream channel, bed material, and depth. For example, outcroppings of bedrock or tree roots close to the sediment surface prevent the chamber from properly sealing and would thus make the site unsuitable for SOD measurements. Finally, seven watersheds/measurement sites were selected. All sampling sites had an established forested riparian buffer on both sides of the stream.

Water Quality Measurements

Water temperature, pH, turbidity, oxygen reduction potential (ORP), and DO were measured with YSI® (Yellow Springs, OH) model 6820 and 6920 water quality sondes. Data were recorded at five-minute intervals with a YSI® handheld microcomputer (models: 650, 610-D, and 610-DM) connected to the sondes. The sondes contained the following probes: 6562 DO probe, 6561 pH probe, 6565 pH/ORP probe, 6560 conductivity/temperature probe, and either a 6036 (non-wiping) or a 6026 (wiping) turbidity probe. Ambient stream conditions for all parameters listed above were recorded at the beginning of each test. While the SOD chamber experiments were in use, stream cross-section, depth, and velocity were measured to calculate an average volumetric flow-rate during the test. Volumetric flow-rate was calculated using the rectangular method of integration. Flow velocity was measured with a Marsh-McBirney®, Inc. portable water flowmeter, model 2000. All equipment was calibrated regularly per manufacturer specifications.

Sediment Oxygen Demand Chambers

The SOD chambers used in the study were designed by Murphy and Hicks (1986) and were on loan from Georgia EPD. Two to three chambers were used at each site to measure oxygen depletion in the sediment matrix while a fourth chamber was used as a control and measured oxygen depletion in the water column.

All chambers remained in the stream for three hours. Throughout the study, the SOD chambers were deployed between 11:00 and 12:00 and were removed from the stream between 14:00 and 15:00.

The aluminum chambers had a volume of 65.15 l and covered a surface area of 0.27 m^2 on the stream bottom. They consisted of three pieces – the ring or main body of the chamber, the cutting edge, and a top or lid (Figures 3 and 4). The cutting edge and lid bolted to the ring. The ring was 18 cm tall and had an inner radius of 46 cm. It also had 5 cm outward-facing flanges at the top and bottom. The lid and cutting edges were bolted to these flanges. The cutting edge was 5 cm long and had a matching outward-facing flange at the top and a sharpened edge at the bottom. Once bolted to the ring, the cutting edge was used to facilitate pushing the ring into the benthic sediments. Good installation required the cutting edge flange to be pushed up against the benthic sediments which meant that the cutting edge was buried at least 5 cm deep in the sediments (Figures 2 and 4). This prevented water from leaking into or out of the chambers through the sediments. The lid had a 22.5 cm long, 13 cm diameter pipe welded to its bottom side (Figure 4). When the lid was bolted to the ring, this pipe extended into the bottom sediments and thus created an annulus within the chamber.

Water in the chamber was circulated around the annulus by a 12 V DC submersible pump (March, 893-04), powered by a submersible, gel-cell, lead acid battery. The pump continuously withdrew water from an intake port installed in the side of the pipe at the center of the annulus (Figures 2 and 4) and injected the water back into the chamber via the two diffusers located 180° apart within the annulus (Figures 2 and 4). This configuration forced the water within the chamber to circulate around the chamber annulus, thus promoting continuous mixing and also somewhat simulating streamflow. We were not able to successfully measure flow velocity within the chamber at the time of the study.

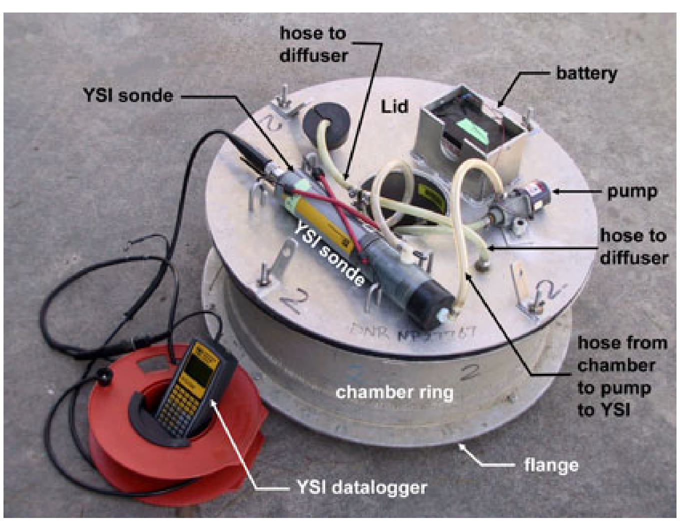

FIGURE 3. Photograph of an SOD Chamber Used in This Study Showing the Main Components of the System Used to Measure SOD Rates.

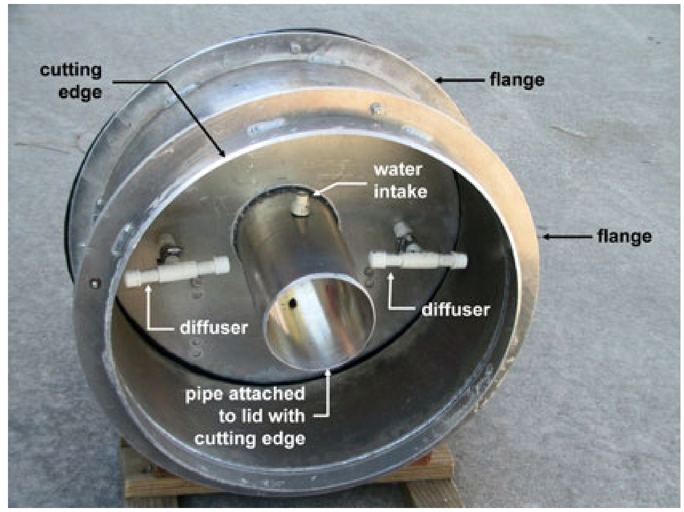

FIGURE 4. Photograph of the Underside of an SOD Chamber Showing the Two Diffusers, the Lower Flange and Cutting Edge Used to Ensure Proper Installation, and the Pipe Welded to the Inside of the Lid, Which Converts the Inside of the Chamber Into an Annulus.

Between the pump and the diffusers, the water passed through a plastic cup covering the probes attached to the YSI® sonde. Thus, the YSI® sonde was able to continuously monitor DO concentration in the chamber as well as several other parameters. The YSI® sonde itself was strapped to the top of the chamber lid. The control chamber differed from the SOD chambers because the bottom of the chamber was sealed off from the sediment, therefore only the oxygen depletion due to the water column (BOD) was measured over the course of each deployment.

Steps for Deploying SOD Chambers

One day prior to each field test, all YSI® sondes were inspected and calibrated. At the site, the depth of the stream was measured to ensure that it was within our operational parameters. Streams had to be at least 30 cm deep to ensure that the chambers were completely submerged but no deeper than approximately 70 cm to allow us to install the chambers and the associated equipment without diving. While checking the depth of the stream, the sediment was also checked for bedrock or large quantities of tree roots that could prevent the chamber from sealing completely. Bedrock was not a problem at any of the study sites; however, tree roots and other large woody debris were a problem at the study sites in the Little River and Upper Suwannee HUCs. Next, the chamber rings were placed in the stream, and the bottom of each chamber was checked to make sure the flange was flush with the stream sediment. It was important to minimize sediment re-suspension, especially under low flow conditions, while examining the stream and deploying the chambers.

The stream's current was allowed to wash any re-suspended sediments downstream from the chambers before the chambers were covered and sealed. The control chamber was installed upstream from the other chambers to minimize the amount of disturbed sediments in suspension around it. Because it was a control, it was important to avoid any sediment deposition in the chamber before it was sealed – the control chamber's purpose is to measure the oxygen demand of the water column immediately above the sediments. Any re-suspended sediment settling into the bottom of the control chamber will erroneously increase the measured water column oxygen demand. After the batteries were attached and the pumps were running, the YSI® sondes were attached to the chambers. The YSI® sondes were programmed to run for three hours and record data every five minutes.

The study sites were visited two to four times during the study period from July, 2004 to April, 2005. However, we were not able to visit the sites during August and September 2004 and again in March and early April 2005 due to high water levels. Between the months of October and March all sites were visited monthly, and measurements were attempted at all sites before the next rotation began. Also, depending on the condition of the equipment, either two or three SOD chambers were deployed each time. The control chamber, however, was deployed during each test.

Calculation of Sediment Oxygen Demand

Sediment oxygen demand is derived from the slope of the linear section of a measured oxygen depletion curve (Figure 5). The small non-linear section at the beginning of the curve is disregarded when completing the linear regression of the data. This region corresponds to initial re-suspension of the sediment during deployment of the chambers and is not an accurate measurement of the natural rate (Caldwell and Doyle, 1995). On average, this region included the first 10-30 minutes of the test. The simple linear regression was completed to get the largest correlation coefficient (R^2 value) possible, which was normally above 0.9 (Figure 5). SOD was calculated using (Murphy and Hicks, 1986; Truax *et al.*, 1995).

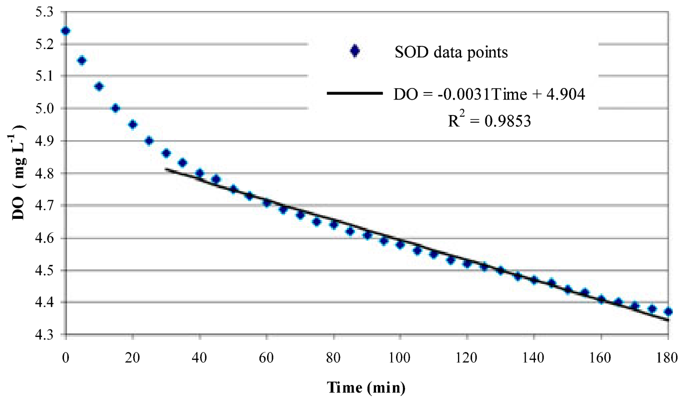

FIGURE 5. An Oxygen Depletion Curve Collected From the Alapaha River Agricultural Study Site on 5 October 2004. A trend line was fitted to the linear portion of the depletion curve and its slope used to calculate SOD rate with Equation (1).

$$\mathrm{SOD} = 1.44\frac{V}{A}(b_1 - b_2), \tag{1}$$

where SOD is the sediment oxygen demand in g O_2/m^2/day; b_1 is the slope from the oxygen depletion curve in mg/l/minute; b_2 is the slope from the oxygen depletion curve of the control chamber in mg/l/minute; V is the volume of the chamber in l; A is the area of bottom sediment covered by the chamber in m^2, and 1.44 is the a units conversion constant (Caldwell and Doyle, 1995).

Once SOD is calculated, it is temperature corrected to 20°C using a modified van't Hoff form of the Arrhenius equation (Equation 2) and an appropriate literature value for the constant θ (Hatcher, 1986; Truax *et al.*, 1995). Values for θ are given by Bowie *et al.* (1985) but the value most commonly used is 1.047. This is the same value used when DO models are applied in Georgia and was the value selected for this study.

$$\mathrm{SOD}_r = \mathrm{SOD}_{20}\theta^{T-20} \tag{2}$$

Sediment Analysis

A particle size distribution analysis was completed on sediment cores collected from each experimental sites. Five cm diameter cores were collected from the top 13 cm of the sediment. Samples were collected around each of the SOD chambers after deployment, and mixed before being stored in a cooler. Samples were refrigerated after returning to the laboratory until the analysis could be completed. The hydrometer procedure for particle-size analysis as described by Gee and Bauder (1986) was used. Organic matter in each sample was destroyed using hydrogen peroxide; the percentage organic matter was calculated by the difference in the dried sample before and after the hydrogen peroxide treatment. All large debris (sticks) was removed from the sample before mass was recorded and the procedure begun.

Statistical Analysis

Sediment oxygen demand levels in the Alapaha River, Little River, and Upper Suwannee River 8-digit HUCs with forested or agricultural land use were tested with an analysis of variance (Proc Mixed and Proc GLM; SAS Institute Inc., 1990). All tests completed in SAS met the requirements of a normal distribution and equal variances. To compare agricultural and forested watersheds, the data were log transformed so that data from the agricultural watersheds would meet the assumption of a normal distribution. For the Proc GLM tests, land use and the three 8-digit HUCs were compared. For the Proc Mixed test, HUC and land use areas were treated as fixed effects and sample date was treated as a random effect. Degrees of freedom were adjusted using the Satterthwaite approximation method. Means were separated using Tukey-Kramer mean separation procedures.

Two separate statistical tests were performed on the data in SAS. The Proc GLM analysis assumes balanced experimental design and very little randomness, which does not properly describe the project's experimental design. Some examples of imbalance within the design are: the sites were not all visited the same number of times, there are only two agricultural sites while there are five forested site, environmental factors such as water flow and sediment composition changed throughout the study period. As a result, a mixed model analysis was also run to look at the interaction between land use and 8-digit HUC and account for the some of the randomness.

RESULTS

Temperature-corrected SOD rates varied on average between 0.1 and 2.3 g O_2 /m^2/day for the seven study sites. Table 2 shows a typical dataset created

TABLE 2. Results From the Agricultural Site in the Alapaha River 8-Digit HUC.

		Deployment Average*				DO			
						Initial	Final		
Date	**Measurement**	**Temp (°C)**	**DO (mg/l)**	**Cond (mS/cm)**	**Turb (NTU)**	(mg/l)		**SOD_c** (g O_2/m^2/day)**	**Q (m^3/s)**
5Oct04	Initial conditions	-	-	-	-	-		-	-
	Control	21.2	6.3	0.1	5.6	5.7	5.0	0.4	
	Chamber 1	21.3	5.5	0.2	20.7	5.2	4.4	0.6	
	Chamber 2	21.3	6.2	0.1	51.6	4.2	4.1	0.5	
	Chamber 3	21.3	6.7	0.1	****	5.8	3.8	1.4	
	Average SOD	-	-	-	-	-	-	0.8	
8Dec04	Initial conditions	17.3	7.5	0.1	****	6.6		-	0.1
	Control	17.6	6.3	0.1	****	6.1	6.0	0.1	
	Chamber 1	17.6	5.7	1.0	94.4	10.1	3.9	2.8	
	Chamber 2	17.5	6.2	0.1	142.5	7.2	6.1	0.8	
	Average SOD	-	-	-	-	-	-	1.8	
4Feb05	Initial conditions	6.8	8.0	0.1	2.7	11.0		-	0.3
	Control	7.4	6.5	0.1	11.0	10.8	10.5	0.1	
	Chamber 1	7.5	6.3	0.1	16.1	12.0	13.5	1.8	
	Chamber 2	7.8	5.6	0.3	118.9	10.8	8.5	4.5	
	Average SOD	-	-	-	-	-	-	3.1	
15Apr05	Initial conditions	14.7	8.1	0.1	****	9.1	-	-	0.2
	Control	15.4	6.5	0.1	****	8.7	8.3	0.2	
	Chamber 1	15.9	5.7	1.0	0.1	7.2	8.0	1.4	
	Chamber 2	15.4	6.3	0.1	15.8	–5.1	–4.9	***	
	Average SOD	-	-	-	-	-	-	1.4	

Notes: SOD, sediment oxygen demand; HUC, Hydrologic Unit Code; DO, dissolved oxygen.
*Ambient stream values were taken upon arrival at the study site and do not represent averages.
**Temperature corrected SOD = SOD_c.
***Appears where SOD could not be calculated due to equipment errors.
****Appears where turbidity could not be measured due to equipment errors.

for each of the sites visited during the study. At this particular site, the chambers were deployed four times. Reported temperature, pH, conductivity, and turbidity are the averages of data recorded in the chamber at 5-minute intervals during each deployment. The table also reports the initial and final DO measured in the chamber during deployment. All of the above parameters were measured with the YSI® sondes. SOD_c reported in Table 2 is the temperature corrected rate (corrected to 20°C) calculated from individual chamber measurements.

The minimum recorded SOD_c across the 8-digit HUCs ranged from −0.9 to 1.6 g O_2/m^2/day, the maximum recorded SOD_c ranged from 0.3 to 3.9 g O_2/m^2/day, and the average ranged from 0.1 to 2.3 g O_2/m^2/day (Table 3). The average SOD_c for each site and the average SOD_c for each land use are shown in

TABLE 3. Mean Temperature Corrected SOD Rates (to 20°C) Measured at Each Site and the Number of Visits Per Site.

		Mean SODc (g O_2/m^2/day)		
Site	***n***	**Min***	**Max**	**Overall Mean**
Alapaha River AG	4	0.8	3.1	1.7
Alapaha River FR_1	4	−0.9	1.6	0.6
Alapaha River FR_2	2	−0.2	0.3	0.1
Little River AG	4	0.6	1.4	1
Little River FR	3	0.9	2.5	1.8
Up. Suwannee FR_1	4	1.6	3.9	2.3
Up. Suwannee FR_2	3	1.4	2.7	2

Notes: SOD, sediment oxygen demand.
The Min in this table represents the minimum mean SOD rate measured at each site. Similarly, Max represents the maximum mean SOD rate measured at each site.
*During each site visit, an SOD rate is calculated for each of the chambers deployed. A mean SOD rate is subsequently calculated for each site visit.

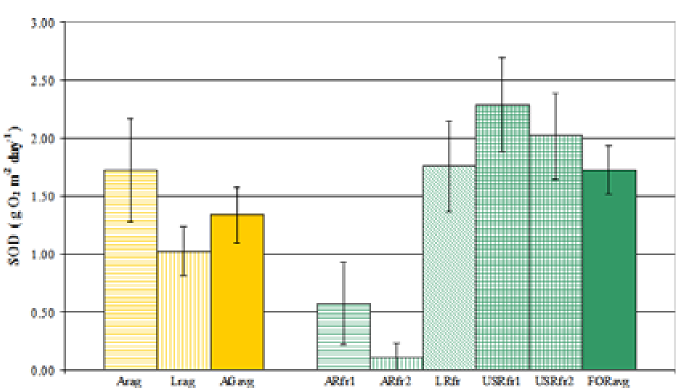

FIGURE 6. Average SOD Values and Error Bars for Each Study Site and Land Use. AR_{ag} is the Alapaha River agricultural watershed. LR_{ag} is the Little River agricultural watershed. AR_{fr1} and AR_{fr2} are the Alapaha River forested watersheds. LR_{fr} is the Little River forested watershed. US_{fr1} and US_{fr2} are the Upper Suwannee forested watersheds. AGavg and FORavg are means of all the individual SOD rates measured for the respective land uses.

Figure 6 along with error bars. Within the results listed in Table 3 are negative SOD rates measured at the two Alapaha River forested sites. The negative values are due to a greater rate of oxygen depletion in the control chamber than in the SOD chambers. Theoretically, a negative SOD value is possible and represents the movement of oxygen from the sediments into the water column. If the chambers are not properly sealed at the cutting edge flange, this may occur. However, we took great care to ensure that a proper seal existed so this explanation is unlikely. Another possible explanation is that instrument (sonde) drift in combination with small changes in DO concentrations within the chamber over the three-hour deployment period resulted in zero or negative values. We have occasionally observed drift with this instrumentation during previous studies.

Statistical analyses found no significant differences between SOD rates at forested and agricultural sites over the entire Suwannee River Basin ($p = 0.214$ for the Proc GLM and $p = 0.5391$ for the mixed test) – a surprising outcome, which contradicted our hypothesis that forested watersheds should have higher SOD rates. Using Proc GLM and comparing HUCs without regard to land use types, the Alapaha River SOD rates were found to be significantly lower than the Upper Suwannee ($p = 0.0216$) (Figure 7). When just the forested watersheds were compared, the Alapaha River forested watersheds' SOD rates were significantly lower than both the Little River ($p = 0.0451$) and Upper Suwannee forested watershed rates ($p = 0.0014$) (Figure 8). The interaction analysis using Proc Mixed Analysis found that there was a significant interaction between HUC and land use ($p = 0.0203$). However, there appeared to be some statistical strength in the interaction between land use and HUC. In other words, there is something intrinsically different in each of the HUCs that

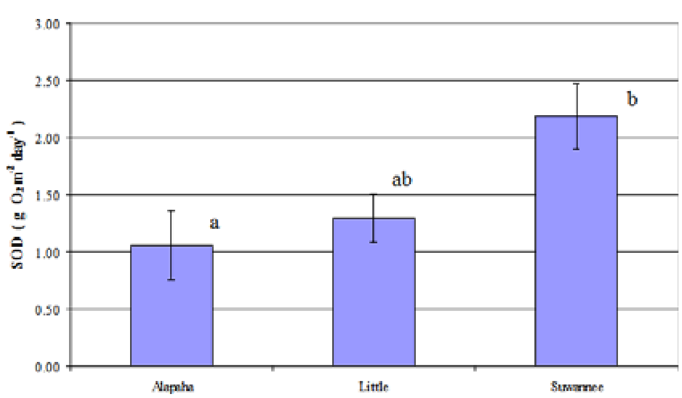

FIGURE 7. Statistical Comparison of HUC SOD Rates in Which Alapaha SOD Rates Were Significantly Lower Than Upper Suwannee SOD Rates. Letters indicate statistically significant differences.

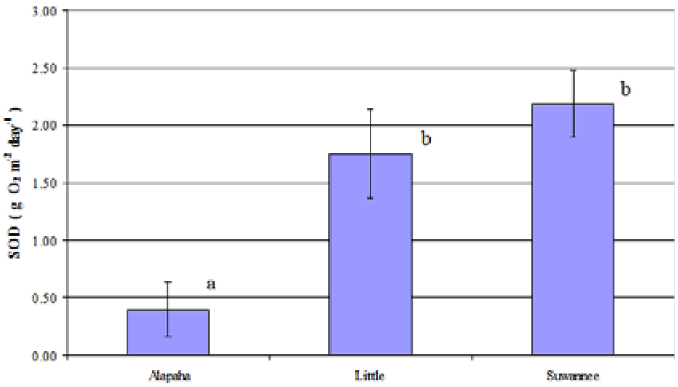

FIGURE 8. Statistical Comparison of Forested Watershed SOD Rates Across 8-Digit HUCs. Alapaha River forested watershed SOD rates were significantly lower than either Little River or Upper Suwannee forested watershed SOD rates. Letters indicate statistically significant differences.

could be affecting SOD and the low concentration of DO within the blackwater streams. This was best represented within the statistical models as an interaction term between land use and HUC.

SOD vs. Organic Matter and Percentage Sand

The results from the particle size analysis are shown in Figure 9. A statistical analysis was run to see if there was a significant correlation between percentage sand, percentage organic matter, and temperature corrected SOD values. Even though trends indicated that, as expected, SOD increased with increasing organic matter and decreased with increasing percentage sand content, no statistical significance was found for SOD rate and percentage sand content (p = 0.2115) or SOD rate and percentage organic matter (p = 0.0623).

Although there was no significant correlation found between percentage sand content and SOD rate or organic matter and SOD rate, the results were marginally non-significant at the p = 0.05 level. It is possible that with a larger sample size the relationship might be stronger. A graphical comparison of sand content to SOD (Figure 10) shows that the two data points from the Upper Suwannee River did not follow the same trend as the remaining data. When the two points from the Upper Suwannee River are removed, there appears to be an inverse relationship between SOD and percentage sand. Furthermore, the correlation coefficient for organic matter to SOD was 73.04; therefore, with a larger sample size, this trend may have been significant. However, other studies have found no statistically significant correlations between SOD rates and sediment characteristics (Seiki *et al.*, 1994; Caldwell and Doyle, 1995).

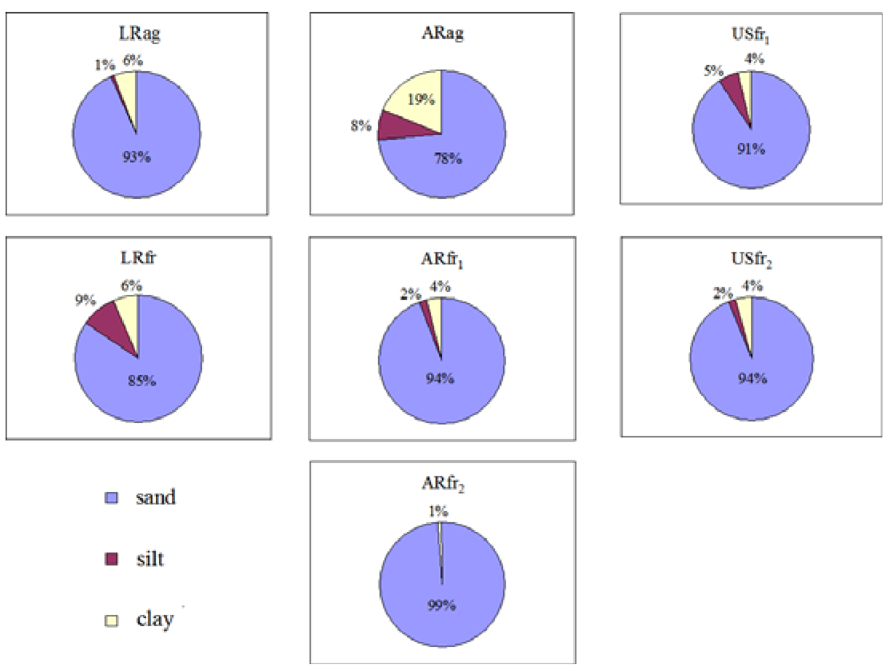

FIGURE 9. Results From the Particle Size Analysis for Each Study Site. AR_{ag} is the Alapaha River agricultural watershed. LR_{ag} is the Little River agricultural watershed. AR_{fr1} and AR_{fr2} are the Alapaha River forested watersheds. LR_{fr} is the Little River forested watershed. US_{fr1} and US_{fr2} are the Upper Suwannee forested watersheds.

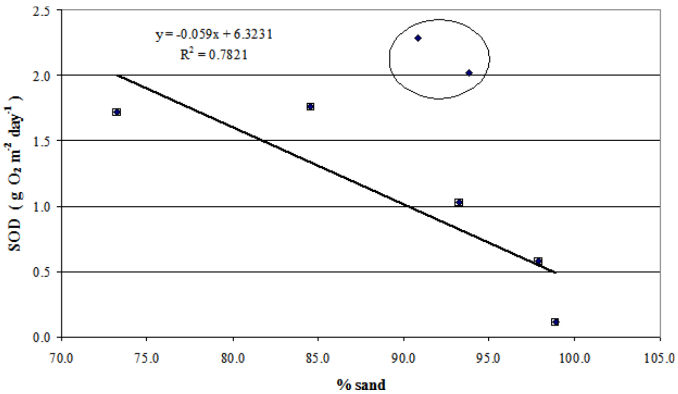

FIGURE 10. Average SOD *vs.* Sand Content. The circled Upper Suwannee River data points have the highest SOD values and the highest organic matter content. A trend is present if the circled points are removed from the dataset.

DISCUSSION

Results from this study showed some unexpected trends. For example, it was expected that on average, agricultural watersheds would have lower SOD values than forested watersheds due to lower rates of allochthonous organic matter. However, we found that in the Alapaha River watershed, the agricultural sites had higher SOD rates than the forested sites. This may be a consequence of higher levels of nutrients, erosion from farming operations, and legacy effects after decades of anthropogenic interference. In contrast, forested sites produced higher rates in the Little River watershed. The Upper Suwannee, a watershed where the majority of the land is densely forested, had the highest average SOD values.

Organic matter was found to be less than 2% of benthic sediments for all experimental sites and negligible at many sites. However, it is possible that a series of hurricanes that passed through our study area during the autumn of 2004 may have flushed much of the benthic organic matter from the tributaries we were studying. In this study, coarse organic debris was removed from the sample before the peroxide treatment of the sediment sample. Therefore, debris such as small sticks or leaves was not included in the mass and percentage organic matter calculations and may have contributed to low calculated values. This coarse debris may have been contributing to SOD through the mineralization process; however it is more likely that the organic debris was of significance to SOD by supplying a food source to microbes in the sediment. Their respiration would be the largest addition to the cumulative SOD.

The highest SOD rates and organic matter concentrations were measured near the Okefenokee Swamp – an area dominated by dense forests, frequently flooded land, and swamps. These features could be the driving forces for higher SOD rates in the Upper Suwannee River HUC and provide further evidence that streams in forested watersheds with fewer anthropogenic impacts may in fact have higher SOD rates.

Comparisons to Values From Literature

Literature values for SOD vary greatly between types of water systems, for example marine, estuarine, and freshwater systems. SOD also varies spatially, for example Eastern U.S. Rivers vary between 0.11 and 0.19 g O_2/m^2/day while Southeastern U.S. rivers range between 0.33 and 0.77 g O_2/m^2/day (Truax *et al.*, 1995). SOD values have also been reported by sediment type. For instance, sandy bottoms range between 0.2 and 1.0 g O_2/m^2/day while mineral soils range between 0.05 and 0.1 g O_2/m^2/day (Bowie *et al.*, 1985). The values from this study averaged between 0.3 and 2.3 g O_2/m^2/day. Considering that the bottom sediments from all of the sites in the study were found to contain greater than 70% sand, the average SOD rates from four of our study sites are considerably above the reported range of SOD rates for sandy bottoms. Five of the sites analyzed in this study also exceed the range listed for Southeastern U.S. Rivers of 0.33 and 0.77 g O_2/m^2/day (Truax *et al.*, 1995). The average SOD value per land use exceeds the range listed for Southeastern U.S. Rivers.

Uncertainty in Values

Sediment oxygen demand values recorded throughout the study only represent brief snap shots of the conditions within a stream reach. However, at the present time these values are the only SOD measurements available for Georgia's coastal plain. Using these values and the relationships found between the HUCs will allow the State to begin looking at the importance of SOD within blackwater streams. Nevertheless, it will be beneficial to continue measuring SOD within the coastal plain and to increase the number of study sites within the Suwannee River Basin to increase the accuracy of extrapolating from study site to stream reach and on to HUC. Although, the values recorded only ranged from 0.1 to 2.3 g O_2/m^2/day and are well below SOD values considered high, these values do exceed ranges currently listed for sandy sediments and streams/rivers within the southeastern U.S. It is not clear if the measured rates could be responsible for the depletion of DO during summer. This is particularly compelling because even though the SOD rates we report have been temperature-corrected, the data were not collected during the summer months.

Comparison of Field Values to Modeled Values for the Coastal Plain

Cathey (2005) and Cathey *et al.* (2005) modeled low DO levels within Georgia's coastal plain, specifically within the LREW – a 334 km^2 watershed contained within the Little River HUC studied in this project. The Cathey (2005) study used experimental data to calibrate and validate the Georgia DOSag model – a steady state, one-dimensional, advection-dispersion, mass-transport, deterministic model which is used by Georgia EPD for DO TMDL development. Most parameters within the model were determined from the data collected within the LREW over the last 20 years. However, SOD and reaeration/turbulence data were not available. Standard equations were used to represent the processes of reaeration and turbulence. Therefore, SOD was left as the equilibrating factor for the model and was modified to calibrate the model. This required a SOD value of around 6 g O_2/m^2/day. During sensitivity analysis, SOD was found to be the most sensitive parameter within the model. However, SOD data from the study reported here indicate that SOD values may be much lower than 6 g O_2/m^2/day. This creates an interesting problem for calibrating the model, as it requires an additional sink for DO or redistribution of the excess uptake.

CONCLUSIONS AND RECOMMENDATIONS

Dissolved oxygen rates in coastal plain streams have been documented to be well below the Georgia DO standards during the summer months. We measured SOD from the fall of 2004 through the spring of 2005; however, measurements were not taken during the warmest time of year from late July through late August. Nevertheless, because the measured SOD rates are higher than those reported in the literature for similar types of streams, it is possible that SOD plays a key role in depleting DO concentration during periods of high temperatures and low flow in the blackwater streams of the coastal plain.

Sediment oxygen demand rates should continue to be measured to build up a database of year round information to be applied to TMDL development and other regulatory actions. When and if funds are available, it would be beneficial to study SOD on the main river channels. However, a dive-certified team would be required to deploy the chambers most of the time, especially during high flow periods. As the need for quality SOD data continues to grow, we believe a measurement technique that can be left *in situ* for long periods of time (months to year round) without constant maintenance should be developed. No matter how much care was taken when deploying the chambers at the study sites, the sediment was greatly disturbed. Developing a long term, *in situ* measurement system could open an important window into understanding the dynamics of SOD and how it should be modeled.

Selecting SOD Values for Models

At the beginning of this study, we hypothesized that associating land use to measured SOD rates could help modelers choose more accurate SOD values. Although there was no significant difference between agricultural and forested watersheds with our current sample size, there were significant differences between HUCs. The finding that environmental parameters are watershed-specific has been reported by other studies in the coastal plain of Georgia (Gregory *et al.*, 1995; Carey *et al.*, 2005).

Sediment oxygen demand values for forested watersheds can be more accurately assigned for DO models by looking at the smaller watershed (Little River, Alapaha, Upper Suwannee, and Withlacoochee) rather than the entire river basin (Suwannee). The high sand content at the Alapaha forested sites and the relatively high organic content at the Upper Suwannee forested sites are easily measured factors that can help modelers pick the most accurate SOD value for their model. Also, comparing measured SOD values to those currently available in the literature for sandy bottom streams or streams in the Southeastern U.S. shows the importance of measuring SOD in the region under question instead of choosing a value from literature based on sediment type or region alone.

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