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MEASUREMENT OF WATER RESIDENCE TIME, FLOWPATH AND SEDIMENT OXYGEN DEMAND IN SEASONALLY INUNDATED FLOODPLAIN SWAMPS OF THE GEORGIA COASTAL PLAIN

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Abstract. Blackwater streams and rivers are found throughout the Coastal Plain of the southeastern United States. These streams are characterized by low slopes, high summertime temperatures, large inputs of dissolved organic material, and extensive inundation of surrounding floodplains. Typically lasting from winter to early spring, the long inundation period creates a multitude of instream swamps and floodplain wetlands that play a vital role in overall water quality. Over 90% of the blackwater streams listed as impaired on the Coastal Plain of Georgia are listed because of violation of the state's dissolved oxygen (DO) standard. Streams are listed as impaired if DO falls below a 4 mg L^{-1} minimum or 5 mg L^{-1} 24-hour average. Generally assumed to be a consequence of increased biological activity from nitrogen and phosphorus enrichment, lowered DO may instead be a natural phenomenon within this system. In an effort to measure the magnitude and influence of floodplain swamps on levels of DO in the river channel, we investigated the residence time, flowpath and sediment oxygen demand (SOD) within a large instream swamp in a representative blackwater river system. Water within one swamp (1550 m in length) had a travel time between 15.5 and 27 hours, with the degree of dispersion highly dependent on flow. SOD is often a critical and dominant sink of oxygen in river systems and despite its importance, is often poorly investigated or estimated in oxygen budgets. Results show SOD rates between 0.87 – 15.84 g O_2 m^{-2} day^{-1}, which is generally higher than values reported in the literature for southeastern sandy-bottomed streams. Coupled with the long residence time, SOD may play a central role in determining DO levels within these instream swamps and for the river system as a whole.

Keywords: Dissolved oxygen, Sediment Oxygen Demand, Residence Time, Blackwater Streams, Water Quality

INTRODUCTION

Blackwater streams and rivers are a common feature of the Coastal Plain of the southeastern United States and are characterized by low slopes, high summertime temperatures, large inputs of dissolved organic material, and extensive floodplain inundation (Meyer, 1990; Smock and Gilinsky, 1992). Typically lasting from winter to early spring, this long inundation period creates a multitude of instream swamps and floodplain wetlands that form a vital link between the terrestrial environment and the river channel and highlights the importance of lateral linkages in a riverine system (Meyer 1990). These instream swamps and floodplains are highly dynamic, changeable entities that while under-studied, likely play a vital role in the water quality of blackwater streams throughout the southeastern United States.

Maintenance of water quality in our nation's waterways is of growing concern, expense, and importance in the United States. In a recent water quality report, 39% of our nation's waterways were impaired for one or more reasons (USEPA, 2002). Within the state of Georgia, 57% of its rivers and streams either partially support or do not support their designated uses (GADNR, 2000-2001). For those streams that do not support their designated uses in the southern Coastal Plain of Georgia, the majority (61 of 68 listed river segments or 90%) are listed due to violation of the state's minimum dissolved oxygen standards of 4.0 mg L^{-1} or 24-hour average of 5.0 mg L^{-1} (GADNR, 2000-2001). Measurement of dissolved oxygen is considered an excellent indicator of stream biological activity and the "most important of all chemical methods available for the investigation of the aquatic environment" (Joyce et al., 1985). With reduced levels of dissolved oxygen, biological activity and biotic integrity could suffer.

Low dissolved oxygen in slow moving streams is generally assumed to be a consequence of increased biological activity from nitrogen and phosphorus enrichment (Suttles et al., 2003). Nutrient enrichment in these systems usually leads to increased algal biomass, dark respiration and biological oxygen demand

(Mallin et al., 2001; Mallin et al., 2004). This phenomenon generally is absent from streams with shading by overhead canopy or when the bottom substrate is loose such as sand. Both of these conditions are common in the listed blackwater rivers and streams in the southeastern Coastal Plain. However, many of the blackwater streams in the Georgian Coastal Plain drain areas of intensive agriculture use that in recent years have supplemented the waterways with additional nutrients through the use of commercial fertilizers that could further exacerbate already low dissolved oxygen conditions (Carey, 2005; Carey et al., 2005).

Low dissolved oxygen levels may indeed be a natural phenomenon of these systems and not a sign of pollution or impairment. Various studies have shown dissolved oxygen levels below the 5 mg L^{-1} limit are common during the summer months even in areas of relatively pristine habitat (Joyce et al., 1985; Meyer, 1992; Ice and Sugden, 2003). Working in the Louisiana South Central Plains, Ice and Sugden (2003) found over 80% of their summertime observations were below the 5 mg L^{-1} standard and close to 60% were below the proposed revised limit of 3 mg L^{-1}. Multiple reasons have been hypothesized for this phenomenon including: high summertime air and water temperatures (Joyce et al., 1985), slow movement of water (Ice and Sugden, 2003), and high inputs of dissolved organic carbon.

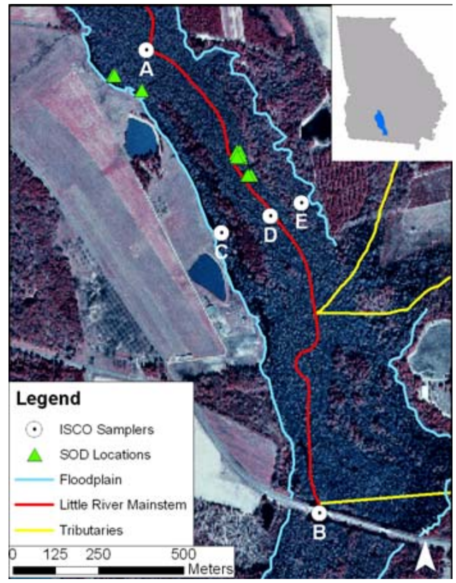

Figure 1. Instream swamp located within the LREW with locations of ISCO samplers and SOD measurement

The reasons for low dissolved oxygen levels are unknown, but are likely due to a combination of the factors listed above. A further sink for dissolved oxygen in this system that has been poorly investigated is the effect of sediment oxygen demand (SOD), or benthic oxygen demand, and specifically within instream swamps and floodplain wetlands. Hatcher (1986a) defines SOD as "the rate that dissolved oxygen is removed from the water column …due to the decomposition of organic matter in the bottom sediments." The literature is consistent in describing SOD as the combination of two processes: 1) Biological respiration of benthic organisms residing in the sediment and 2) chemical oxidation of reduced substances found within the sediment matrix (e.g. Bowman and Delfino, 1980; Hatcher, 1986a; Chau, 2002). The effect of SOD on the oxygen budget of an entire river system should not be under-estimated, as it can be a critical sink of dissolved oxygen (Wu, 1990). Indeed, in some rivers SOD can account for over half of the total oxygen demand and can play a primary role in the water quality of a stream system (Matlock et al., 2003; Rutherford et al., 1991). While being a potentially major influence on the total oxygen demand within a system, this parameter is often assumed or estimated in water quality models (Hatcher, 1986a; Matlock et al., 2003). Errors in this measurement can lead to inaccurate models for the stream environment at great biological and financial cost.

This study attempts to quantify the influence of water movement and SOD on dissolved oxygen levels within a characteristic blackwater instream swamp. Increased travel time and lower water velocities through these streams could lead to lowered dissolved oxygen levels through increased contact time with underlying sediments and little opportunity for reaeration. Despite the potential importance of travel time and residence time, neither has been investigated in blackwater streams or within their expansive instream swamps. SOD is a further way to characterize this influence as increased contact time, higher temperatures, and highly organic sediments could drive down dissolved oxygen levels even during periods of higher flow. By measuring SOD throughout the course of different temperatures and water levels, a more complete view of its influence on dissolved oxygen will be achieved.

METHODS

Study Site

Research was conducted in part of the Little River Experimental Watershed (LREW), a 334 km^2 research watershed of the Southeast Watershed Research Laboratory of the USDA Agricultural Research Service (Sheridan and Ferreira, 1992). Instrumented for the measurement of rainfall and streamflow beginning in 1967, the LREW has been designated as representative of the soils, topography, geography and land use within the southern Coastal Plain. While land use is primarily agricultural, riparian vegetation remains largely intact along portions of the river with swamp hardwood communities consisting of a closed canopy and thick undergrowth. The instream swamp selected for this experiment is a 1550 m long stretch of river located in the lower part of the LREW (figure 1). The stream at this point is a 5th order stream and can be as wide as 350 m during periods of complete inundation. Inundation of the floodplain usually begins in December with complete inundation till April or May. During the summertime months, flow may stop along with complete drying of the river channel.

Sediment Oxygen Demand

SOD was measured using chambers designed by Murphy and Hicks (1986) (Crompton et al., 2006). Each chamber has a volume of 65.15 liters and covers a surface area of 0.27 m^2 on the stream bottom (figure 2). The cutting flange sinks the chamber 5.08 cm (2 in.) into the stream sediment. Water circulates throughout the chamber via a 12 volt DC submersible pump, powered by a 14 volt submersible, gel-cell, lead acid battery. The pump continuously withdraws water from one diffuser and injects it back in the chamber via the second diffuser. The diffusers force the water within the chamber to circulate around the chamber annulus, promoting continuous mixing. The control chamber differs from the experimental chamber by having a sealed bottom which is used to measure water column respiration. Oxygen concentration was measured within the chamber using an oxygen optode (Oxygen Optode 3975, Aanderaa Instruments, Bergen, Norway) logging to a handheld computer (Dell Axim X50, Dell Inc., Round Rock, TX) (Figure 2). For each sampling event, SOD chambers were pushed into the sediment until sealed and then oxygen and temperature levels logged within chambers every five minutes for 2-3 hours. SOD was calculated using:

Figure 2. SOD chamber with datalogging computer

$$SOD = 1.44\frac{V}{A}\left(b_1 - b_2\right) \qquad (1)$$

where:
SOD = the sediment oxygen demand (g O_2 m^{-2} day^{-1})
b_1 = the slope from the oxygen depletion curve (mg L^{-1} minute^{-1})
b_2 = the slope from the oxygen depletion curve of the control chamber (mg L^{-1} minute^{-1})
V = the volume of the chamber (L),
A = the area of bottom sediment covered by the chamber (m^2)
1.44 = a units conversion constant (Caldwell and Doyle, 1995)

SOD rates were then corrected to 20˚C using a modified van't Hoff form of the Arrehnius equation (Hatcher, 1986b; Truax et al., 1995):

$$SOD_{T_c} = SOD_{20}\theta^{(T-20)} \qquad (2)$$

where:
SOD_T = SOD rate at temperature T
SOD_{20} = SOD rate at 20˚C
θ = constant chosen from literature

Values for θ based on the type DO model are given by (Bowie, 1985). Because this project was designed to generate SOD data for use in Georgia, a θ of 1.047 was used.

After deployment, sediment samples from beneath each chamber were taken for analysis of organic matter content, total carbon and nitrogen, and particle size analysis (work ongoing). Before and after each deployment, temperature, pH, conductivity, ambient DO level and percent saturation was measured using a YSI 6920 sonde (YSI Inc., Yellow Springs, OH). A water quality sample was collected in a 1-liter glass bottle for the measurement of nitrate (NO_3^--N), orthophosphate (PO_4-P), ammonium (NH_4-N), total nitrogen (TN), total phosphorus (TP), and dissolved organic carbon (DOC) concentrations.

Rhodamine Dye Trace

Measurement of travel time through the swamp was achieved through the release of rhodamine WT dye (Fluorescent Red, Norlab Inc., Amherst, OH) and the deployment of five automated discrete water samplers (Teledyne Isco 3700, Teledyne Isco Corp., Lincoln, NE). Samplers were placed in the river channel to get a longitudinal as well as a horizontal transect of dye travel time (figure 1). Sampler A was the upstream sampling point. Sampler D was placed in the center of the river 600 m downstream of Sampler A. Two additional samplers (C and E) were placed in a latitudinal transect parallel to Sampler D. A fifth permanent sampler (Sampler B) served as the downstream end of the study reach. A broad-crested V-notch weir at this location was used to measure flow during the experiment. Sampler B is 950 meters below Sampler D giving the entire reach a length of 1550 meters. For each sampling run, rhodamine WT dye was released approximately 6500 m north of Sampler A to ensure adequate mixing of the dye by the time it reached the upstream sampler.

During collection, a 70 mL water sample was taken every fifteen minutes. Four samples were composited into a single bottle giving an hourly average. Bottles were switched out every 24 hours. Upon return to the lab the concentration of rhodamine dye in each sample was measured on a fluorometer (TD-700 Laboratory Fluorometer, Turner Designs, Sunnyvale, CA).

RESULTS

Sediment Oxygen Demand

Sediment oxygen demand was measured multiple times in various locations within the instream swamp (figure 1). Results show rates between 0.87 – 15.84 g O_2 $m^{-2}day^{-1}$, which is generally higher than values reported in the literature for southeastern sandy-bottomed streams (table 1). Measurement of NO_3^--N, NH_4-N, OP, and TP were all below detection limit (<0.2 mg L^{-1}). Both ambient temperature and DOC concentrations within the instream swamp increased over time (table 1). Temperature increased from 15°C in middle March to near 21°C in middle April while DOC concentrations increased from 13.09 mg L^{-1} to 16.36 mg L^{-1} over the same time period.

Table 1. Sediment Oxygen Demand (SOD_{20}), Chamber and Ambient Temperature, Total Nitrogen and Dissolved Organic Carbon Measurements.

Date	Chamb	SOD_{20} (g O_2 $m^{-2}day^{-1}$) Ind	Avg	Chamb. Temp (°C)	Amb. Temp (°C)	Total N (mg L^{-1})	DOC (mg L^{-1})
3/15/06	1	2.982	2.440	15.04 – 17.57	15.90 – 18.09	0.6074	13.09
	2	2.400		15.12 – 17.72			
	3	1.939		15.11 – 17.53			
4/5/06	1	0.870	2.730	16.44 – 17.75	16.75 – 18.73	0.6967	13.93
	2	3.595		16.31 – 17.80			
	3	3.726		16.31 – 17.91			
4/11/06	1	14.965	13.000	15.48 – 17.28	15.98 – 18.13	0.6524	14.56
	2	15.836		15.30 – 16.79			
	3	8.200		15.37 – 17.18			
4/13/06	1	2.112	4.272	17.21 – 18.30	17.04 – 18.96	0.6627	14.55
	2	2.950		17.16 – 18.43			
	3	7.755		17.02 – 18.48			
4/19/06	1	2.102	3.840	20.13 – 20.33	19.97 – 20.84	0.8164	16.36
	2	8.490		20.30 – 20.85			
	3	0.929		20.15 – 20.47			

Rhodamine Dye Trace

Travel time through the instream swamp was determined two different times (table 2). Average daily flows measured at the downstream end of the swamp were much less during the second run and in turn the travel time was nearly twice as long for the entire reach. Dye concentration curves show further differences as the curves show a wider curve with much longer tails in the second run (figure 3a and 3b). In fact, the dye concentration never returns to background concentrations during the second run. During the first run, the side channel samplers (C and D) show a peak in concentration a few hours after sampler D and characteristic concentration decline curves. The second run exhibits less characteristic curves with dye concentrations in the side channels not reaching a noticeable peak with little differentiation between background concentrations. Using flow volumes and dye concentrations measured at B, a mass balance of the dye was calculated for each tracer run. The calculations indicated the mass balance of Dye Trace 1 and Dye Trace 2 were 7.89% and 2.49% respectively.

Table 2. Average daily flow and travel time through a seasonally inundated instream swamp

	Dist (m)	Date	Avg. Daily Flow (m^3s^{-1})	Travel Time (hrs)
Dye Trace 1		1/24/06 – 1/30/06	2.63 — 4.14	
Inj. Point to to A	6500			26
Sampler A to D	600			5
Sampler D to B	950			10.5
Total Reach	1550			15.5
Dye Trace 2		3/29/06 – 4/7/06	0.32 — 1.01	
Inj. Point to to A	6500			43
Sampler A to D	600			11
Sampler D to B	950			16
Total Reach	1550			27

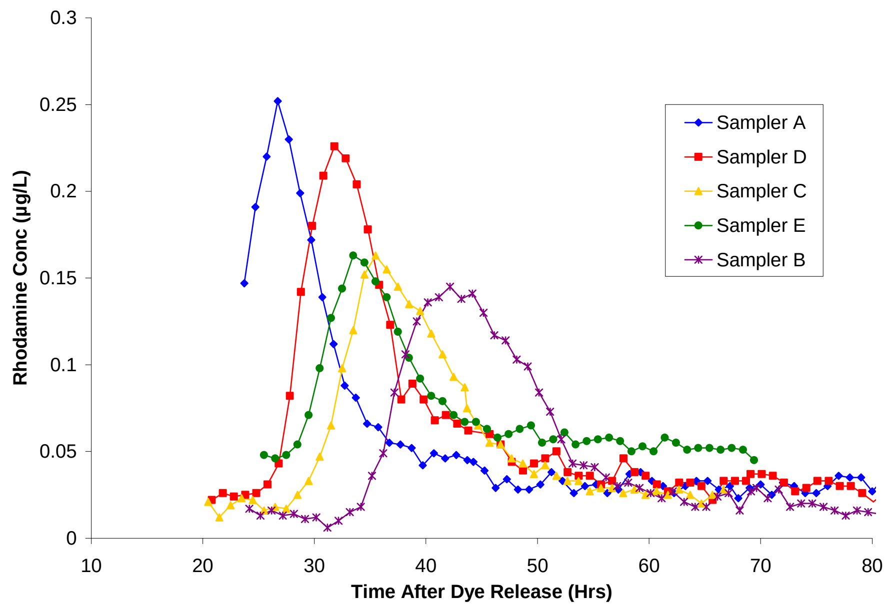

Figure 3a. Rhodamine dye concentration over time during first travel time run

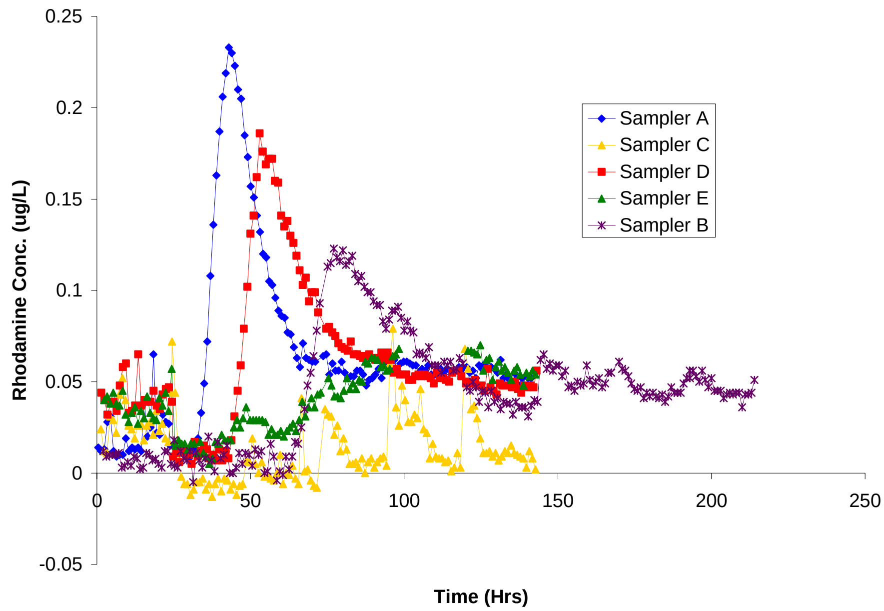

Figure 3b. Rhodamine dye concentration over time during second travel time run. Notice difference in scale.

CONCLUSION

Previous research in the LREW has shown that accurate measurement of SOD is the most important variable to accurately predict DO levels (Cathey et al., 2005). Despite the importance of accurate measures of SOD, it is oftentimes estimated from literature values because of the difficulty in obtaining SOD measurements. Truax et al. (1995) state that SOD rates for Southeastern United States rivers range between 0.33 – 0.77 g O_2 $m^{-2}day^{-1}$. None of the SOD measurements in this study fall within that range as all measures are higher and in some cases much higher (up to 48 times) than previously published values. Further, a previous study measuring SOD within forested and agricultural catchments of the LREW found SOD rates between 0.6 – 1.4 g O_2 $m^{-2}day^{-1}$ in the agricultural catchment and 0.9 – 2.5 g O_2 $m^{-2}day^{-1}$ in the forested catchment (Crompton, 2005) . Greater than half of the measures made in the instream swamp during this study (table 1) are above the highest value recorded during the previous study. These results indicate that SOD may play an even greater role than previously thought in the LREW. This is the first time SOD has been measured in one of these instream swamps and these results suggest they are areas of intense oxygen demand and are a major factor in the oxygen balance of the watershed as a whole. Further work investigating the composition and organic matter content of the sediments within these instream swamps will further elucidate the role these swamps are having in the total oxygen demand for the river system as a whole.

Travel time through these instream swamps was also an unknown factor within this system. It has been hypothesized that the slow movement of water coupled with oxygen demand from the underlying sediments help to drive down oxygen concentrations within the water column. Further, previous research in a regulated riverine swamp system in Louisiana showed that the three dimensional flow of water through its floodplains significantly influenced the dissolved oxygen dynamics (Sabo et al., 1999). As shown above, the first part of this experiment exhibited high SOD rates throughout the swamp. Travel time was measured twice with the first run being a period of relatively high flow and the second being a period of almost no flow. Not surprisingly, travel time increased with decreasing flow. However even during a period of relatively high flow (Dye Trace 1), travel time was still over 15 hours for a distance of 1550 m. During the period of lowered flow, travel time was nearly twice as long. Additionally, concentrations of rhodamine dye never returned to background levels during the second dye run (figure 3b), indicating that under lowered flow conditions dispersion is increased and some of the water remains in the system for long periods of time. This lowered flow and increased travel time was in concert with SOD measurements that were higher than previously reported literature values. Longer travel time allows for more contact between the sediments and the overlying water column which could in turn lower dissolved oxygen concentrations. To gain a better understanding of the travel time dynamics within this system, additional measurements must be made under a variety of flow conditions.

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