DYNAMICS OF OXYGEN DEMAND WITHIN THE MIDDLE AND LOWER SAVANNAH RIVER BASINS

Oscar P. Flite III, Patrick Smith, Aaliyah Green, and Jason W. Moak

AUTHORS: Oscar P. Flite, III, Southeastern Natural Sciences Academy, 1858 Lock and Dam Road, Augusta, GA, 30906
Patrick Smith, Southeastern Natural Sciences Academy, 1858 Lock and Dam Road, Augusta, GA, 30906
Aaliyah Green, Southeastern Natural Sciences Academy, 1858 Lock and Dam Road, Augusta, GA, 30906
Jason W. Moak, Southeastern Natural Sciences Academy, 1858 Lock and Dam Road, Augusta, GA, 30906

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Abstract. Ensuring dissolved oxygen (DO) concentrations remain above a certain critical minimum is important for sustaining healthy riverine systems. Since rivers worldwide are typically undersaturated with respect to DO and oversaturated with respect to carbon dioxide (CO_2), it is clear that oxygen loss mechanisms override oxygen production mechanisms in rivers. The predominant loss mechanism is bacterial respiration of carbonaceous and ammoniacal substrates. These substrates originate from both natural and human derived sources and have a range of bacterial degradation rates so some are broken down quickly while others require longer processing periods. Understanding DO dynamics within rivers is further complicated by the temporal-spatial dynamics as a single mass of water flows through various land use types toward a terminal water body. Each land use type contributes a myriad of substrates that can stimulate aerobic bacterial respiration resulting in loss of DO. The location of the exertion of oxygen loss along a river length as a result of a particular source is then a function of the input location, the exertion rate, and the river flow. In order to ensure that critical DO minima are met along an entire river length, it is therefore important to understand the juxtaposition of these parameters in order to resolve low DO concentrations within a particular stretch of river.

This study was designed to assess the temporal-spatial dynamics of oxygen demanding substances along 200 river miles of the mainstem Savannah River basin. We sampled the mainstem of the Savannah River on a bimonthly basis from several of 12 permanent monitoring stations as well as several natural and human derived sources. For each sampling event, a Lagrangian sampling scheme (repeatedly sampling the same mass of water at multiple locations according to travel time) was used for the mainstem river samples which allowed an opportunity to assess effects due to land use differences. We used a 120 day bottle incubation period (GAEPD protocol) to determine the oxygen consumption rates and ultimate DO loss for each of the samples.

Results of the Lagrangian sampling consistently showed that there was not a steady increase or decrease in ultimate oxygen consumption or consumption rates with downstream flow but showed that consumption changed with changing land usage. The data also showed that oxygen demand trends at a single site over time varied from 15-75%. These data indicate that further research is necessary in order to better characterize the sources of oxygen demanding substances within the Savannah River.

INTRODUCTION

Maintaining good water quality is important for sustaining healthy ecosystems and vibrant economies. When water quality decreases, both ecology and economy are imperiled. Since the survival of most aquatic organisms is dependent upon maintaining DO concentrations within specific limits, and many natural and anthropogenic discharges to surface waters have an impact on DO, DO is one of the most important water quality parameters; it is often where aquatic ecology and economy intersect.

Assuring that DO concentrations remain within certain limits requires an understanding of gain and loss mechanisms. In rivers, gain of DO is often attributed to reaeration and photosynthesis while loss of DO is often attributed to bacterial respiration. Respiration of organic material consumes oxygen and generates CO_2. Since rivers are usually oversaturated with respect to CO_2, it is clear that respiration dominates photosynthesis in these systems (Cole and Caraco, 2001). It is therefore necessary to determine the sources of energy that fuel bacterial metabolism if there is any chance of managing dissolved oxygen concentrations in rivers.

Biochemical Oxygen Demand (BOD) is a laboratory test that helps determine the oxygen consuming potential of energy sources within a water sample. The relatively straightforward procedure assesses total oxygen loss from a water sample that is stored in a sealed bottle and incubated for a certain time period. Length of incubation time is determined by the assessment goals. Since longer incubation times often require significantly more resources, shorter times are often employed. Drawbacks to the shorter time period are decreased data resolution for curve fitting, inability to attribute specific DO loss due to individual constituents, and incomplete oxidation of most constituents within the sample.

Once a series of DO versus time data is established, the line can be analyzed with several different curve-fitting procedures so characteristics of the DO consuming substrates within the sample can be understood. Due to the consumptive nature of the test (with respect to the substrates), the data often generate an asymptotic curve. Therefore, a first order equation is often used to describe the data. Parameters of the first order equation are then used to make assessments of the energy substrates within the sample and also allow for an opportunity to model DO consumption downstream of where the sample was collected. Usually effluents and river samples are comprised of a myriad of substances that have potential to fuel bacterial respiration so a single curve does not adequately represent the data. Theoretically, there should be a curve for every substance within the sample and once superimposed, the final curve would perfectly represent the data. Since this approach is impossible it is common practice to use multiple curves to create a single, additive curve that better approximates the data. Currently, EPA and GAEPD have incorporated a more complex, dual-first order curve fitting analysis in order to better characterize and model oxygen demanding substances related to the current Total Maximum Daily Load assessment within the Savannah River. Therefore, we used the same curve fitting approach for this study. The integrated, two-component first order differential equation is:

$$BOD_u = BOD_1(1 - e^{-k_1 t}) + BOD_2(1 - e^{k_2 t})$$

where,
BOD_u = ultimate BOD demand at time t (mg/L)
BOD_1= BOD demand due to component 1
BOD_2= BOD demand due to component 2
k_1 = rate of DO consumption for component 1 (1/d)
k_2 = rate of DO consumption for component 2 (1/d)
t = time (d).

Since material within both natural and manmade discharges to rivers can serve as energy sources for bacterial respiration, it is necessary to determine the origin of those sources and the temporal-spatial dynamics of the system in order to determine cause and effect relationships. This study was designed to assess the temporal-spatial dynamics of oxygen demanding substances along 200 river miles of the mainstem Savannah River basin. The study is currently ongoing so a subset of the data is presented here.

METHODS

Study Area

The Savannah River flows through three physiographic provinces (Blueridge, Piedmont, and Coastal Plain), has three large hydropower reservoir projects, and three additional dams; the river is free-flowing after ~RM 187. The Middle Savannah River Basin (MSRB) begins downstream of J. Strom Thurmond Dam (JST) and the Lower Savannah River Basin (LSRB) begins near RM 61. Since the water that feeds the MSRB originates from the metalimnion of Thurmond Lake, it has unique water quality characteristics if compared to a similar distance within an unimpounded river. Therefore, this discharge represents a unique “land use type” (reservoir). Downstream of the reservoir (RM 222), the Central Savannah River Area (CSRA) represents a typical urban land use type which begins ~RM 210 and ends ~RM 179. From ~RM 179 to ~RM 40, the lowlands are mostly bottomland hardwood swamps and the uplands are predominantly agriculture and pine forests. Within the tidal section of the river, the city of Savannah is characterized by an urban land use type which begins below RM 40. Twelve permanent sampling sites were selected within the MSRB and LSRB. Locations of these mainstem sites ranged from RM 215 (~7 river miles below Thurmond Dam) to RM 27 (I-95 bridge). Additional sites were also sampled throughout the study period in order to characterize various natural and manmade discharges to the river.

Sampling scheme

River samples were collected bi-monthly from several of the mainstem sampling sites; most of those samples were collected according to a Lagrangian sampling scheme. Due to the complexity of regulated flows and tidal influences, samples were collected while water was discharging from the dam (RM 215) and while water was flowing either upstream or downstream (RM 27). Samples were collected in triple rinsed 20 L carboys, stored on ice until arrival at the lab, and refrigerated until processing.

Ultimate-BOD sample preparation and determination

We followed an EPA amended (John Marlar, personal communication, 2009) methodology developed by GAEPD (1999) for determination of uBOD. In short, all samples were divided into a ground glass stoppered, 2 L BOD bottle and a 1 L reservoir bottle after being homogenized with a churn splitter. All samples and reservoir bottles were incubated at 20° C for 120 days. DO was checked daily for the first week, once every other day during weeks 2 and 3, every third day during weeks 4-6, and weekly for the remaining time period. If needed, samples were reaerated before the DO reached 4 mg/L by vigorously shaking the entire 3 L sample for 30 seconds among two BOD bottles. In order to determine DO loss due to nitrification, ~4 mL of sample was removed from each bottle on each day the DO concentrations were assessed. Nitrate, nitrite, and ammonia concentrations were determined using an AQ2 discrete autoanalyzer (SEAL Analytical, Mequon, WI) while TKN was assessed on day 1 and day 120 by permanganate digestion and subsequent ammonium analysis on the AQ2. All data were entered and analyzed within GAEPD's (2008) LtBod software program (version 3.0.).

RESULTS

In general, there was no steady increase or decrease in uBOD or rates of oxygen consumption with downstream distance. The most general trend in uBOD data for all sampling events was a small, steady increase from RM 215 to RM 185, a large increase at RM 179, a large decrease through RM 119, and a steady increase to nearly the same concentrations observed at RM 179 (Fig. 1).

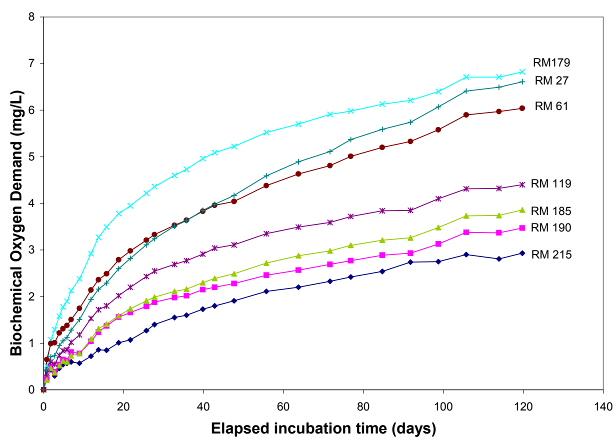

Figure 1. Ultimate-BOD sample results from June 2009 Lagrangian sampling event.

Statistics on five important BOD parameters (k_{fast}, k_{slow}, $uBOD_{fast}$, $uBOD_{slow}$, and uBOD) for several sites are presented in Table 1. Although the data indicated that RM 215 had nearly half the k_{fast} as all other sites, that the k_{slow} and $uBOD_{fast}$ values were nearly the same, and that RM 190 and RM 27 had high $uBOD_{slow}$ values compared to sites immediately upstream, the variability of the data, was quite high. Coefficient of Variation (CV) values ranged from 5.4% to 82.9%, with an average value of 43.1% for all data presented in Table 1.

Table 2 shows the partitioning results of uBOD data between k_{fast} and k_{slow} for the June 2009 Lagrangian sampling event. Data indicated that the lake discharged water that was best characterized by a single first order fit equation and had a k-value of 0.016/d, a rate consistent with slow reacting material which meant that k_{slow} was equal to 100% of the material. Through the urban land use section of the river, k_{slow} decreased to 86.6%. Through the floodplain wetland and agricultural land use sections, k_{slow} steadily decreased to 77.3%. In the final urban/wetland land use, k_{slow} increased to nearly 83%.

Average k_{fast} and k_{slow} rates for each site were lower than the rates used by EPA and GAEPD in the RIV-1 model to characterize the Savannah River, except at RM 61 which had a slightly higher k_{fast} average (0.154/d) (Fig. 2).

CONCLUSIONS

This research showed that intra-site variability for all BOD parameters was high (from 5%-83%). Since duplicate samples analyzed during each sampling event had an average variability of 6% (data not shown), it is believed that the high variability resulted from the stochastic nature of riverine systems. Although we have not yet assessed correlation of BOD trends to other limnological variables, the transition from several

Table 1. Ultimate-BOD statistics for several sites.

	RM215	RM190	RM61	RM27	Brier Ck (~RM90)	Estuary	Harbor (~RM11)
Average							
k_{fast}	0.076	0.122	0.154	0.131	0.042	0.057	---
k_{slow}	0.014	0.009	0.011	0.013	0.005	0.010	0.025
$uBOD_{fast}$	0.820	1.224	1.482	1.335	1.760	2.430	---
$uBOD_{slow}$	3.230	7.902	4.940	6.818	11.950	4.210	3.780
uBOD	4.050	9.126	6.422	8.153	13.710	6.640	3.780
Standard Deviation							
k_{fast}	0.023	0.065	0.050	0.051	---	---	---
k_{slow}	0.007	0.007	0.005	0.009	---	---	---
$uBOD_{fast}$	0.453	0.599	0.758	0.547	---	---	---
$uBOD_{slow}$	0.176	4.313	1.265	2.988	---	---	---
uBOD	0.628	4.912	2.023	3.535	---	---	---
Coefficient of Variation							
k_{fast}	29.8	53.5	32.5	39.2	---	---	---
k_{slow}	46.5	82.9	41.2	67.6	---	---	---
$uBOD_{fast}$	55.2	48.9	51.2	40.9	---	---	---
$uBOD_{slow}$	5.4	54.6	25.6	43.8	---	---	---
uBOD	15.5	53.8	31.5	43.4	---	---	---
n	**3**	**5**	**5**	**4**	**1**	**1**	**1**

consecutive years of drought within the Savannah River basin to a relatively wet year would seem to be a significant source of the variability. This research also points to the importance of conducting multiple sampling events in order to understand the variability of a dynamic system instead of assuming that the system is static.

A significant advantage of using a Lagrangian sampling scheme (June 2009) was the ability to determine sources, fate, and transport dynamics of BOD while the same parcel of water flowed through different land use types. As shown in Figure 1, the lake discharged BOD, the urban corridor slightly more than doubled that incoming BOD which was then partially attenuated by RM 119; leaving a net increase of ~60% to RM 119. Relative to RM 119, BOD increased by ~50% to RM 61 and ~63% to RM 27; these increases were believed to result mostly from natural discharges to the river. The CSRA marks the beginning of the Coastal Plain which is characterized, in part, by organically rich, tannic streams. We sampled Brier Creek in order to determine the contribution of BOD from a strictly Coastal Plain system and found the highest BOD concentrations of all sampled river sites (~14 mg/L).

Table 2. Percentage of uBOD partitioned between k_{fast} and k_{slow} components for June 2009 Lagrangian sampling event (actual rates varied across sites).

	k_{fast} (%)	k_{slow} (%)
RM 215	0.0	100.0
RM 190	12.2	87.8
RM 185	13.4	86.6
RM 119	21.0	79.0
RM 061	22.7	77.3
RM 027	17.1	82.9

Although Brier Creek is an open channel which drains a sub-watershed of the Savannah basin, it is probable that the extensive wetlands adjacent to the river, beginning ~RM190, contribute similar BOD loads through hyporheic exchange; this is a topic for future research efforts.

Besides an assessment of uBOD dynamics, the Lagrangian scheme also allowed for an assessment of the partitioning of uBOD between k_{fast} and k_{slow} with decreasing river mile. Since the lake essentially discharged 100% k_{slow} material (k = 0.016), all additions of k_{fast} material resulted from the remaining land use types. Again, assuming Brier Creek represented a typical Coastal Plain system, the k_{fast} partition was ~13% which was similar to that contributed through the urban land use type. The wetland/agricultural land use type contributed nearly 70% more k_{fast} material to the system which was significantly higher than the Brier Creek partition ratio. This most likely resulted from an uncharacterized source of fast acting BOD to the river along that reach. The same was most likely true for the transition from RM 61 to RM 27 because k_{slow} increased to ~83% which was well beyond the 64% ratio for the estuary characterization which we presumed to be the dominant source in that river reach.

Decay rates ranged from 0.076/d to 0.154/d for k_{fast} and 0.009/d to 0.014/d for k_{slow}. Nearly all of the data were

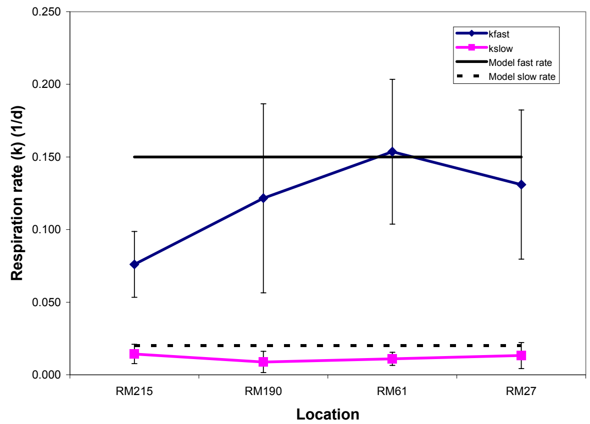

Figure 2. Average k_{fast} and k_{slow} for several sampling sites. Solid and dotted horizontal lines indicate fast and slow river rates used in RIV-1 model, respectively.

below the rates used in the model efforts related to the pending TMDL. Depending upon the residence time of the system and location of natural and manmade discharges, this could have significant implications for determining the impact of individual discharges on the low DO critical zone.

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