The Calibration, Validation, and Sensitivity Analysis of DOSag, an In-Stream Dissolved Oxygen Model

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THE CALIBRATION VALIDATION AND SENSITIVITY ANALYSIS OF GEORGIA DOSAG: AN IN-STREAM DISSOLVED OXYGEN MODEL

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ABSTRACT

Eighty four percent of dissolved oxygen (DO) impaired streams in Georgia occur within five physiographic regions: the Tifton Upland, Vidalia Upland, Okefenokee Basin, Bacon Terraces, and the Barrier Islands Sequence. Such a high number poses the question; is the average daily level of DO in these streams naturally less than the water quality standard of 5.0 mg L^{-1}? Streams in southern Georgia display several characteristics causing low levels of DO. Typically, the streams have low gradient channels, experience high temperatures and low to zero flow in the summer, and initial evidence shows that sediment oxygen demand (SOD) may be high.

Georgia DoSag version 2.1 has been used by the Georgia Environmental Protection Division to model DO and develop Total Maximum Daily Loads (TMDLs) in the Altamaha River Basin. DoSag will continue to be used to model DO as a part of Georgia's TMDL program. The objective of this research was to determine the applicability of DoSag in coastal plain streams. This paper describes the parameter estimation, calibration, sensitivity analysis, and validation of the DoSag model in the Little River Experimental Watershed (LREW), located in the coastal plain of Georgia. The result of this paper describes a matrix of dominant causes of low DO conditions in the LREW including SOD, reaeration, temperature, and streamflow. An understanding of natural versus anthropogenic causes for low DO will not be fully understood until SOD and reaeration in Georgia's coastal plain are measured.

KEYWORDS. Dissolved oxygen, DoSag, calibration, validation, sensitivity analysis, long-term BOD, TMDL

INTRODUCTION

Dissolved oxygen (DO) it is one of the constituents regulated by the Clean Water Act (1972) and the Total Maximum Daily Load (TMDL) program. The Georgia Environmental Protection Division (EPD) requires that all streams maintain: "A daily DO average of 5.0 mg L^{-1} and no less than 4.0 mg L^{-1} at all times for waters supporting warm water species of fish" (Georgia EPD, 1999). This load was set for the benefit of fishes and other aquatic life that require DO. The EPD understands that some waters may not be able to meet these standards naturally. They go on to state that natural levels of DO can be understood through the use of computer models.

Eighty four percent of DO impaired streams in Georgia occur within five physiographic regions: the Tifton Upland, Vidalia Upland, Okefenokee Basin, Bacon Terraces, and the Barrier Islands Sequence (Figure 1). This unusually high number of violations in one area raises the question as to whether the level of DO in these streams is naturally less than 5.0 mg L^{-1}.

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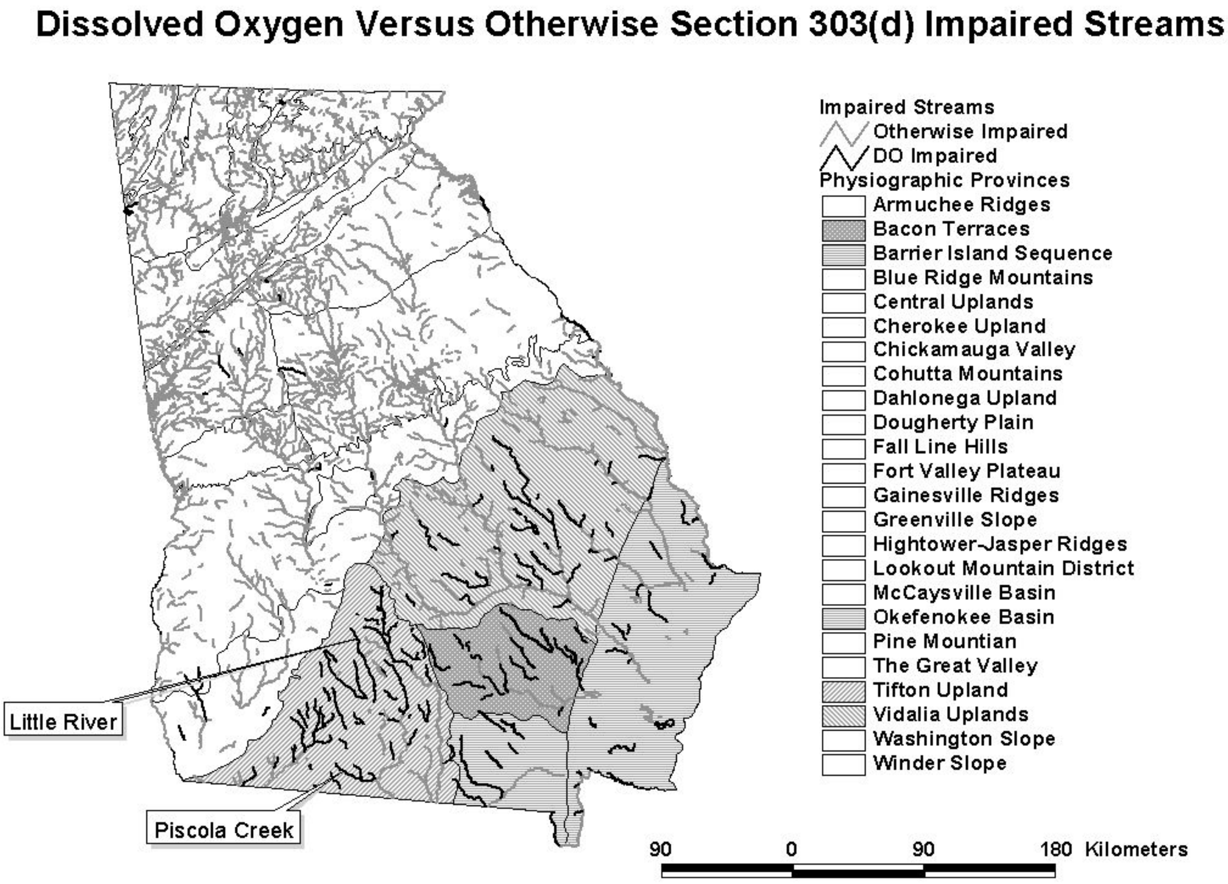

Figure 1. EPA physiographic regions (U.S. EPA, 2004) and 303-d listed DO impaired streams in Georgia. The black streams are DO impaired, the gray streams are otherwise impaired.

Georgia's coastal plain is not the only region facing widespread violations of DO standards. Ice and Sugden (2003) showed that in Louisiana, during August 2001, 81% of sampled least-disturbed streams had dissolved oxygen levels below 5.0 mg L^{-1}. They suggested that the low levels of DO were due to low gradient, low flow, and high sediment oxygen demand (SOD). McIver and Mallin (1999) also found low levels of DO in the Cape Fear watershed, located in the coastal plain of North Carolina. In their study, annual mean levels of DO ranged between 3.3 and 10.1 mg L^{-1}. The McIver and Mallin study concluded that high temperatures and oxygen demanding substances from both natural and anthropogenic sources were responsible for the hypoxic conditions.

The EPD plans to use DoSag to model naturally occurring DO in streams in the southern coastal plain of Georgia. The model has already been used by the EPD to model DO and develop TMDLs in the Altamaha River Basin. DoSag uses a modified version of the Streeter-Phelps equation (Streeter and Phelps, 1925) to calculate DO stepwise through a stream network. It is a steady-state, one-dimensional, advection-dispersion, mass-transport, deterministic model. DoSag was developed by Dr. Roy Burke of the Georgia EPD in the late 1980's. There is no peer reviewed documentation describing the model.

The objective of this research was to determine the applicability of DoSag in coastal plain streams. The first step was to estimate parameters that affect DO. The model was then calibrated, analyzed for sensitivity, and validated. Finally, recommendations for future parameter estimation and modeling techniques in the coastal plain of Georgia were made.

The site selected for the application of DoSag was the Little River Experimental Watershed (LREW). The LREW occupies 334 km^2 and is located in the Suwannee River Basin of the costal plain of Georgia. The watershed is one of six regional USDA research watersheds and is considered typical for the coastal plain area (Sheridan and Ferreira, 1992).

PARAMETER ESTIMATION

The DoSag model contains many parameters, rates, coefficients, and processes that dictate the quantity of the state variable, dissolved oxygen. Parameters estimated for this research included water temperature, streamflow, depth, velocity, channel slope, reach length, watershed area, reaeration, DO saturation, biochemical oxygen demand (BOD), SOD, photosynthesis, respiration, and the concentration of DO in water flowing into each reach. The following paragraphs describe how each of these parameters was estimated for model input.

The LREW was skeletonized into a set of subwatersheds in ArcView (ESRI; Redlands, CA) (figure 2). USGS digital elevation maps and hydrologic datasets were used to delineate these subwatersheds. The watershed was skeletonized to create discrete areas into which parameters were input and could be varied. ArcView was used to calculate the area, reach length, and reach slope for each subwatershed.

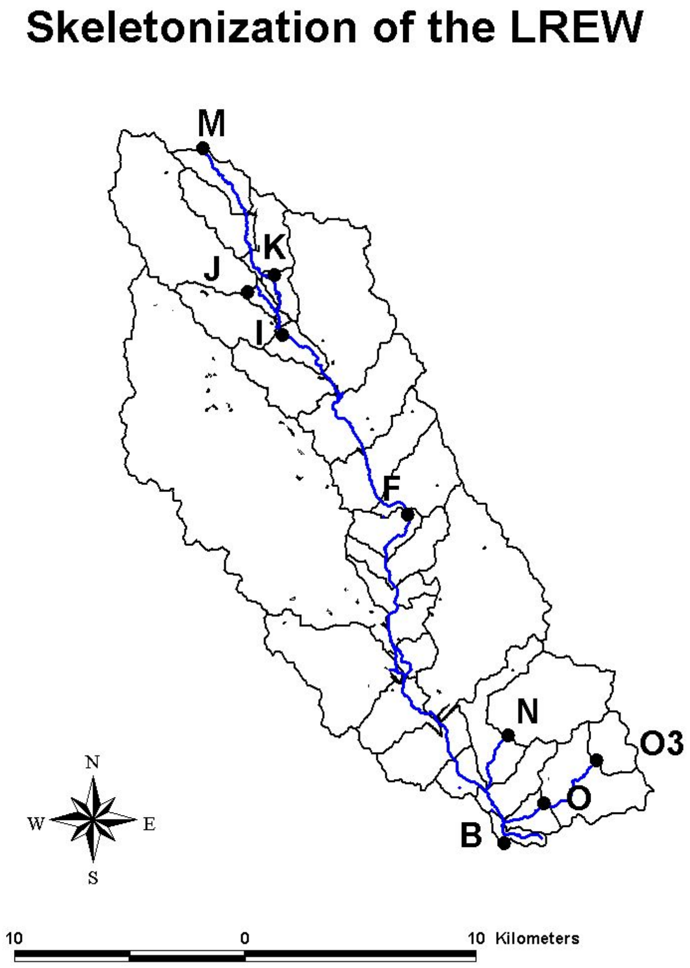

Figure 2 The skeletonization of the LREW. The letters indicate the locations of the sampling/gauging stations.

Flow was calculated from stage data collected at eight weirs in the LREW. Flows were input into each subwatershed based on a proportioned water yield. Natural stream cross-sections were surveyed upstream from the gauging stations to estimate stream depth. Average depth on each modeling day was then calculated by raising or lowering the water line in the cross-section according to stage data. A mass balance of flow was assumed between the cross-section and the stage recorders. This allowed the calculation of velocity from the cross-section and flow data according to the continuity equation.

DoSag mixes lateral and upstream flow at the head of each reach. Each of these flows carries with it a load of DO which must be incorporated into the model. The percent saturation of DO in upstream flow was calculated internally by the Streeter-Phelps equation. Lateral flow is the additional flow that enters a reach between its inlet and outlet. DO in lateral flow is a user input and was assumed to be equal to the measured DO at the nearest downstream monitoring station.

Reaeration was calculated internally in DoSag using the O'Connor Dobbins equation (O'Connor and Dobbins, 1958). This equation calculates a reaeration rate based on average velocity, depth, and the diffusivity of oxygen in water.

Long-term biochemical oxygen demand (BOD) tests were conducted to measure carbonaceous biochemical oxygen demand (CBOD) and nitrogenous biochemical oxygen demand (NBOD). The long-term test is similar to the standard five-day BOD test, but it takes 120 days, the stream water is undiluted, and the samples are periodically reaerated and tested for DO and nitrogen. The ultimate NBOD, CBOD, and the associated degradation rates were all calculated directly from the long-term test.

The chlorophyll *a* equation (Thomann and Mueller, 1987) was used to calculate oxygen production through net photosynthesis. The equation assumes that oxygen production by phytoplankton in stream water can be calculated given a mass of chlorophyll per liter of water and various other environmental conditions including day length, the extinction coefficient, and solar radiation. The chlorophyll *a* equation was paired with the respiration equation (Thomann and Mueller, 1987) to calculate the net photosynthetic production of DO.

In the absence of measured SOD values from the LREW and because of the wide range of published SOD values from other areas, the value for SOD was estimated. This was done by measuring all other known parameters and fitting a value for SOD based on the unaccounted DO.

CALIBRATION

Calibration is the process of adjusting parameters to make modeled DO match the values measured in the field. The parameters that were estimated were fine-tuned during calibration. DoSag does not have an automatic calibration option. Therefore, calibration was performed using a trial-and-error method. Model calibration was conducted by sequentially calibrating various parameters; flow was calibrated first followed by velocity, CBOD, NBOD, and finally DO. Table 1 summarizes the parameters used in the final calibration.

Table 1. Calibrated parameters

Parameter	Calibration Value
Ultimate CBOD	*17 mg L^{-1}
Ultimate NBOD	**1.7 mg L^{-1}
CBOD degradation rate	0.04 d^{-1}
NBOD degradation rate	0.13 d^{-1}
SOD	6 g m^{-2} d^{-1}
Water temperature	11.64 - 12.86°C
Net photosynthesis	1.5 mg L^{-1} d^{-1}
Depth	0.23 – 0.57 m
Velocity	0.018 - 0.16 m s^{-1}
Water yield	3.63 – 10.84 L s^{-1} km^{-2}
DO	3.29 – 9.13 mg L^{-1}

* A value of 6.0 mg L^{-1} was used in the headwaters.

** A value of 0.5 mg L^{-1} was used in the headwaters.

SENSITIVITY ANALYSIS

Sensitivity analysis is the process of varying parameters within published or reasonable ranges and observing how those changes affect the model output.   This exercise was conducted to reveal how sensitive the model was to changes in parameters. The parameters were increased and decreased by 0, 25, 50, 75, and 100 percent. The results of the most sensitive parameters are graphed in figure 3. SOD, reaeration, depth, and velocity were the most sensitive parameters. Though flow was not directly analyzed for sensitivity, velocity and depth are indirect indicators of flow.

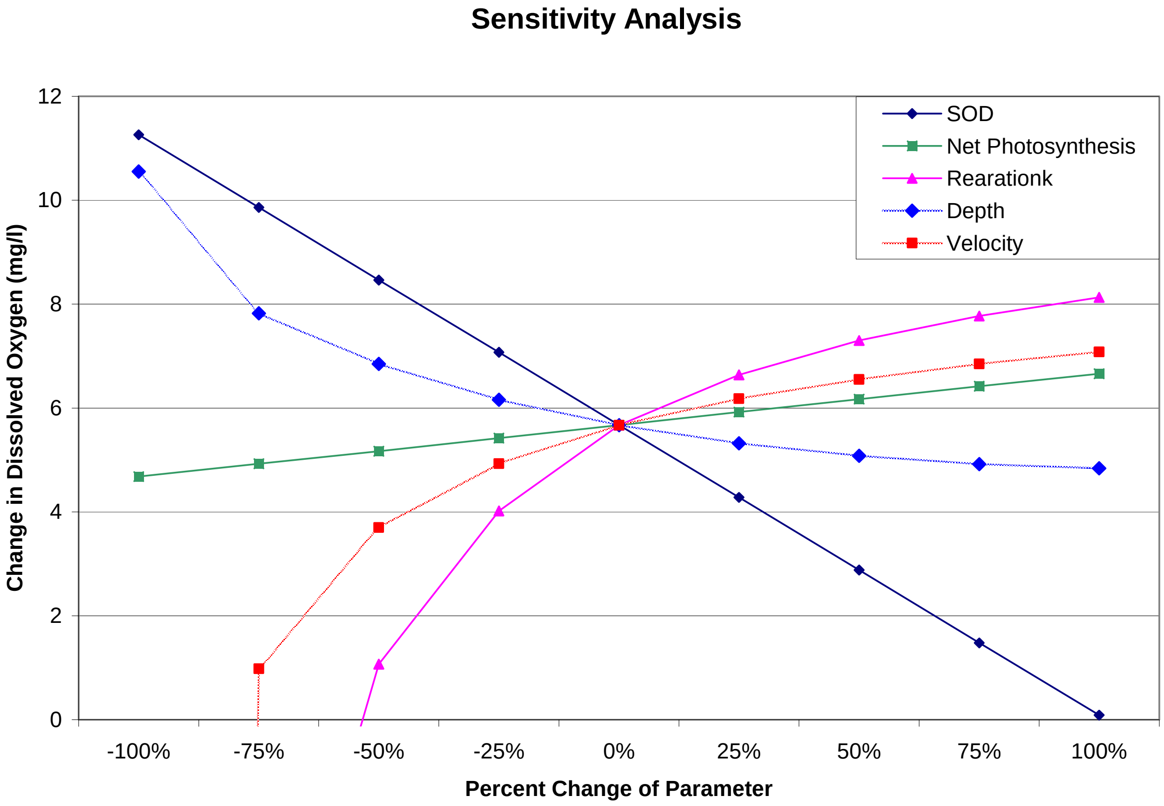

Figure 3. Results of the sensitivity analysis are shown for the outlet of the LREW. Only the most sensitive parameters are presented.

VALIDATION

Validation is the process of running a calibrated model under different conditions to see if the model continues to represent the system. DoSag was validated in nine scenarios including both temporal and spatial validations. The temporal validations were conducted on days with varying temperatures, flows, and levels of DO. The spatial validations were conducted on the Piscola Creek Watershed (figure 1). The Piscola Creek is a 390 km^2 watershed located south of the LREW. Both the LREW and the Piscola Creek Watershed lie in the EPA's Tifton Upland ecoregion (U.S. EPA, 2004).

The differences between the modeled and measured DO were used to gauge the accuracy of each validation run. The absolute value of the true error of DO averaged between all of the gauging stations per scenario is shown in table 2. This error ranged between 0.57 and 2.56 mg L^{-1}. High temperatures and low flows correlated to high errors. The scenario with the largest average error was also the scenario with the highest temperature. The scenario with the second highest error was the scenario with the lowest flow. These errors indicate the conditions which are not appropriate for obtaining accurate model outputs.

Table 2. Selected parameter values for each validation run ordered by DO error. The calibration date is shown at the top to serve as a baseline.

Date	Site	Water temp (°C)	Flow (L s^{-1})	Sampled DO (mg L^{-1})	Average absolute error of DO (mg L^{-1})
		Data collected at Station B (figure 2)			
3/12/2004	LREW	12.7	1394	6.6	0.91
3/9/2004	Piscola	*12.2	*4300	*7.7	0.57
4/24/1996	LREW	17.7	1218	3.9	0.84
4/22/1993	LREW	16.3	1008	5.0	1.03
4/18/1996	LREW	20.8	2756	4.1	1.06
10/18/1996	LREW	20.2	890	2.3	1.22
3/16/2004	Piscola	*18.2	*3500	*6.5	1.25
5/9/1996	LREW	24.0	1246	3.1	2.10
5/12/1997	LREW	17.8	155	2.8	2.23
9/2/1994	LREW	27.5	574	2.6	2.56

* Average of sampled values in the Piscola Creek

DISCUSSION AND CONCLUSION

Larger modeling errors appear to be associated with low flow and high temperatures (Table 2). Although it was expected that low flow scenarios would be associated with large errors because of the relationship between velocity and reaeration, the fact that high temperatures were associated with large errors was surprising. This may be because temperature is a variable in several parameters including, DO saturation, SOD, BOD and net photosynthesis. The use of temperature in so many equations may have compound errors associated with it.

Figure 4 shows that DO concentrations dropped to negative values when reaeration or velocity approached zero. These negative concentrations are not possible in the physical world. Furthermore, in the model, water with a negative concentration of DO requires more oxygen to reach a positive concentration than water with zero DO. The negative concentrations were a result of SOD continuing to be exerted regardless of the DO concentration. Modifying the model in a way that prevents negative concentrations appears necessary. Although negative DO is not an issue in streams with continuously high levels of DO, in areas where waters are regularly hypoxic or anoxic, negative concentrations of DO will impact the validity of the model results.

SOD was assumed to be the oxygen demand that was left after all other known variables were calculated. This method for estimating SOD assumed that all other parameters were known and measured accurately. Though this technique was useful for calibration, it may have concealed sampling errors in other parameters and therefore may not represent the true SOD exerted in the system. SOD is currently being measured in the LREW. These values will be available for future modeling efforts.

The Georgia EPD has developed and will continue to develop TMDLs for Georgia's coastal plain using the DoSag model. To date, most applications have been on stream segments with point sources that affect DO. The question remains of whether DoSag is appropriate for establishing DO TMDLs on streams segments without point sources. To answer this question, we preformed the following exercise. The Little River, the main channel in the LREW is 303(d) listed for DO impairments. In the calibrated LREW model, BOD was completely removed from the system. As a result, the DO only increased by 0.3 mg L^{-1} at the end of the model. Considering the fact that DO in the LREW regularly falls well below 4.0 mg L^{-1}, the elimination of all BOD would not be enough to take this stream off of the 303(d) list. Therefore, assuming that all parameters were properly estimated, the stream should be considered naturally low in DO.

However, because of the inexact method that was used for establishing SOD, the value that was used for SOD in the model may not correspond to the value in the real system. If the question of natural levels of DO is to be addressed then SOD must first be properly quantified. If the modeled SOD value of 6 g m^{-2} d^{-1} proves to be representative of the system, then the exercise explained in the previous paragraph should indicate that the LREW is naturally low in DO. If the 6 g m^{-2} d^{-1} value for SOD proves to be artificially high, then the model must be recalibrated and the exercise in removing BOD should be repeated. If the DO in the stream still does not drop significantly then the stream may again be considered naturally low in DO.

If DO does increase significantly when BOD is removed in a calibrated model containing the new SOD values then setting a TMDL will involve dividing BOD between anthropogenic and natural sources. This can be done two ways. The first way involves calibrating DoSag in reference streams with minimal anthropogenic impacts. 303(d) listed DO impaired streams can then be modeled using the calibrated reference stream parameters that are vulnerable to anthropogenic impacts. Parameters, which may be anthropogenically impacted, include BOD, SOD, net photosynthesis and temperature. The model output from the impaired stream, using the previously mentioned reference stream parameters, can be analyzed to determine if DO in the impaired stream remains low or increases.

The second way of proportioning anthropogenic and natural BOD involves looking at landscape processes. Natural nonpoint source pollution is a result of organic material entering a stream through leaf litter fall, runoff, and in-stream processes. Anthropogenic nonpoint source pollution in agricultural areas is largely a result of nitrate and phosphate runoff from fields. If a stream is nutrient limited, then the input of nutrients will increase algal growth and may lead to eutrophication. If this stage is reached in the TMDL process, then the use of DoSag should be reevaluated. Dynamic landscape processes cannot be modeled in DoSag; it is purely a steady-state in-stream model. Steady state effects of landscape processes on DO can be modeled if those processes are externally computed. Other programs such as SWAT and HSPF are capable of modeling dynamic landscape processes and can be used to model the entire system or generate inputs for the DoSag model.

The former discussion needs to be considered with the larger limitations of the model in mind. Because of the nature of the Streeter-Phelps equation, DoSag cannot be used to model no-flow conditions. When velocity goes to zero reaeration is severely limited. No-flow usually occurs during the summer months when the stream temperatures are also high. No-flow and high temperatures are the seasonably varying conditions under which DO falls to the lowest levels. A modeling effort can show that the streams are either naturally or anthropogenically low in DO if they drop to low levels under flowing conditions. But, a modeling effort cannot prove that streams are naturally or anthropogenically low in DO if they only drop to low levels under the no-flow conditions that cannot be modeled.   So, natural levels of DO under the most critical seasonal conditions cannot be fully understood through modeling.

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