

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

by

ANNA M. CATHEY

(Under the Direction of Matt Smith and George Vellidis)

ABSTRACT

Eighty four percent of dissolved oxygen (DO) impaired streams in Georgia occur within five physiographic regions in the coastal plain. This high number of violations in one area poses the question; is the natural level of DO in these streams less than the minimum set by the state? Streams in southern Georgia display several characteristics responsible for low levels of DO such as low gradient channels, high temperatures, and low to zero flow. The Georgia Environmental Protection Division plans to use a program called DoSag to model natural levels of DO in these streams. The objective of this research was to determine the applicability of DoSag in the coastal plain. This paper describes the parameter estimation, calibration, sensitivity analysis, and validation of the model in the coastal plain of Georgia. The paper's conclusion discusses a matrix of dominant causes of low DO including: sediment oxygen demand, reaeration, temperature, and streamflow.

INDEX WORDS: Dissolved oxygen, DoSag, calibration, validation, sensitivity analysis, long-term BOD, TMDL, parameter estimation

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## Chapter 1: Introduction

The Georgia Environmental Protection Division (EPD) is currently reviewing streams in the southern coastal plain of Georgia, which are listed on the U.S. Environmental Protection Agency's (EPA) section 303(d) list of impaired water bodies. Ninety one percent of impaired streams in four river basins in Georgia (Satilla, Saint Mary's, Suwannee, and Ochlocknee) are in violation of the minimum daily average of  $5.0 \text{ mg L}^{-1}$  for dissolved oxygen. This unusually high number of violations in one area raises the question as to whether the level of dissolved oxygen (DO) in these streams is naturally less than  $5.0 \text{ mg L}^{-1}$ . If these streams are naturally low in DO, an understanding of the natural levels and the mechanisms responsible for low DO could lead to more appropriate regulations for the region.

According to the EPD, natural levels of DO can be understood by modeling impaired streams under pristine conditions. The EPD plans to use a program called DoSag to model DO in these streams. DoSag has already been used by the EPD to model DO and develop DO Total Maximum Daily Load (TMDL) in the Altamaha River Basin. The model was developed by Dr Roy Burke of the EPD. There is no peer reviewed documentation describing the DoSag model.

The objective of this research was to provide insight into the factors responsible for low DO in coastal plain streams and to indicate the applicability of the DoSag model in coastal plain streams for the TMDL program. In order to do this, the parameters that

affect DO were estimated. The model was then calibrated, analyzed for sensitivity, and validated. Finally, recommendations were made for future data collections and modeling techniques that would optimize modeling in the coastal plain of Georgia.

## Chapter 2: Literature Review

### Description of Total Maximum Daily Loads

According to the U.S. Clean Water Act (1972), states are required to set water quality standards for stream and rivers. If a stream does not meet a water quality standard, it is assumed that the load applied to a stream is too great. The stream is then placed on the EPA's section 303(d) list of impaired streams. The total maximum daily load (TMDL) is the maximum amount of a single pollutant that can enter a water body without compromising water quality standards. TMDLs must be developed for streams that violate the standards set by the state.

Dissolved oxygen (DO) it is one of the constituents regulated by TMDLs. Adequate levels of DO are important for sustaining fishes and other aquatic life (EPD, 1999). Many parameters affect the level of DO in a stream, including the amount of organic material present. Organic material can be naturally occurring or introduced through human activities. Other factors affecting DO levels include temperature, reaeration, and sediment oxygen demand (SOD).

### Treatment of waters not meeting water quality standards

The EPD requires that all streams maintain "A daily DO average of  $5.0 \text{ mg L}^{-1}$  and no less than  $4.0 \text{ mg L}^{-1}$  at all times for waters supporting warm water species of

fish” (EPD, 1999). However, it is understood that some waters may not be able to meet this standard. The EPD went on to state:

“It is recognized that certain natural waters of the State may have a quality that will not be within the general or specific requirements contained herein. This is especially the case for dissolved oxygen, temperature, pH, and fecal coliform” (EPD, 1999).

The U.S. EPA further quantified requirements for streams that do not meet the standard:

“Where natural conditions alone create dissolved oxygen concentrations less than 110 percent of the applicable criteria means or minima or both, the minimum acceptable concentration is 90 percent of the natural concentration” (EPA, 1986).

Natural conditions were defined by the EPD as:

“Those that would remain after the removal of all point sources and water intakes, would remain after removal of man made or induced nonpoint sources of pollution, but may include irretrievable effects of man’s activities, unless otherwise stated” (EPD, 1999).

#### Coastal plain dissolved oxygen violations

Many coastal plain streams violate the EPD’s DO standards. Eighty four percent of DO impaired streams occur within five physiographic regions located in the coastal plain: the Tifton Upland, Vidalia Upland, Okefenokee Basin, Bacon Terraces, and the Barrier Islands Sequence (Figure 1). With respect to river basins, 91 percent of DO impaired streams in four river basins occurred in the southern coastal plain of Georgia:

the Satilla, St. Mary's, Suwannee, and Ochlocknee (EPD, 2002). Either way, such a high number of violations in one area raises the question: is the average daily level of DO in these streams naturally less than the standards proposed by the EPD?

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 percent of sampled least-disturbed streams had dissolved oxygen levels below 5.0 mg L<sup>-1</sup>. For their study, least-disturbed streams were defined by being Outstanding Resource Waters, Natural and Scenic Rivers, inside a National Wildlife Refuge, or containing visibly intact riparian areas. The study suggested that the low levels of DO were due to low gradient, low flow, and high sediment oxygen demand.

The Cape Fear watershed is located in the coastal plain of North Carolina. McIver and Mallin (1999) found that DO in this watershed's streams was also low. In their study, annual mean levels of DO ranged between 3.3 and 10.1 mg L<sup>-1</sup>. They stated that two factors worked synergistically to create the hypoxic ( $1 \text{ mg L}^{-1} < \text{DO} < 5 \text{ mg L}^{-1}$ ) conditions; waters with high temperatures have a low capacity for holding oxygen in solution, and oxygen demanding substances, from both natural and anthropogenic sources, lower the levels of DO in the system.

#### Computer models and the TMDL program

There are several methods that the state can use to determine if a stream is naturally low in dissolved oxygen. According to the EPD:

“Natural conditions shall be developed by an examination of historic data, comparisons to reference watersheds, application of

# GA EPD's Section 303-d Listed Streams

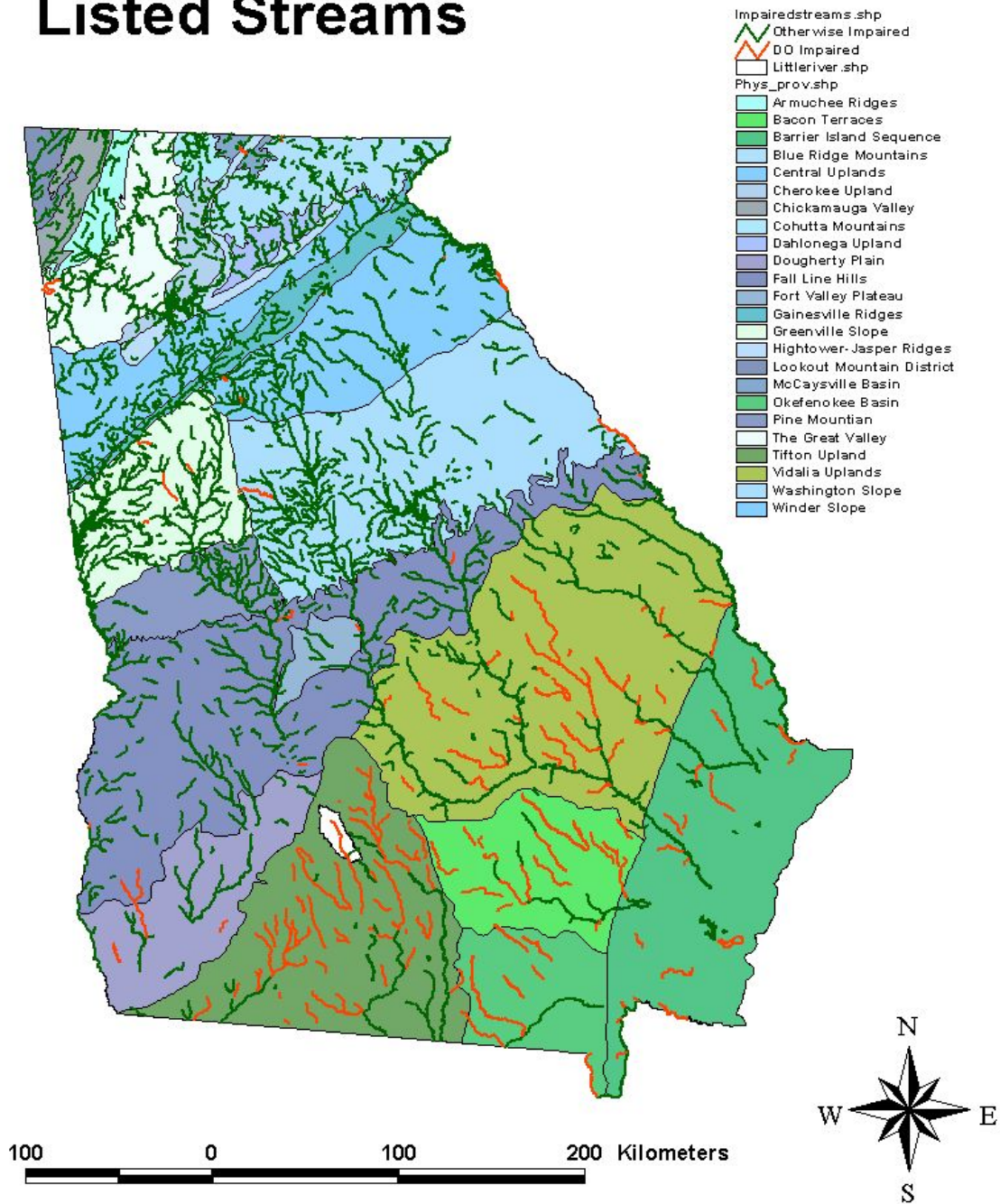


Figure 1. EPA physiographic regions and 303(d) listed DO impaired streams in Georgia. The red streams are DO impaired, the dark green streams are otherwise impaired. Note the aggregation of DO impaired streams in the southern coastal plain.

mathematical models, or any other procedure deemed appropriate by the Director” (EPD, 1999).

There are contemporary datasets of water quality in coastal plain streams. However, a historical dataset that could be used to interpret the natural levels of DO in these streams is not available. Such data would have to predate large-scale agriculture and urbanization as well as reflect the changes that a stream underwent as it experienced anthropogenic point and nonpoint impacts. Natural conditions can also be determined through comparisons with reference watersheds. Reference watersheds are watersheds that can be considered relatively free of anthropogenic impacts. A National Wildlife Refuge may be considered a reference watershed. The only National Wildlife Refuge in the Georgia’s coastal plain that is not tidally influenced is the Okefenokee National Wildlife Refuge. The Okefenokee’s hydrology is not typical for the coastal plain because of the vast swampy nature of the area. So, for the purposes of this study, a reference watershed was unavailable. Computer modeling may also be used to understand the naturally occurring levels of DO in streams. The advantages of modeling include the ability to model any time or place and being able to compartmentalize natural and anthropogenic influences on DO.

#### *The choice of using DoSag for this research*

There are many programs available for modeling DO in streams, including DoSag (Burke, 2004), QUAL2E (Brown and Barnwell, 1987), ISIS (Cox, 2003), MIKE-II (Cox, 2003), and WASP5 (Ambrose et al., 1995). The variety of models is a result of individual studies developing custom-made and often site-specific models. Each of these programs contain limitations and assumptions which are important when choosing

a model and interpreting the results. Cox (2003) reviews several models that are used for in-stream DO modeling. The models vary from simple to complex. Major differences between the models include variations in the mathematical quantification of parameters, steady state versus dynamic models, and deterministic versus stochastic models.

The DoSag model is used by the EPD to model DO in rivers for the National Pollution Discharge Elimination System (NPDES). DoSag has been used to model DO in the Altamaha river basin (EPA, 2001) and will be used to model DO in small rivers in the future (Burke, 2004). The DoSag model was chosen for this research because the EPD will make regulatory decisions based upon its outputs.

#### Description of DoSag

DoSag was developed by Dr. Roy Burke of the EPD in the late 1980's (Burke, 2004). The model is based on a modified version of the Streeter-Phelps equation (Streeter and Phelps, 1925). It is a steady-state, one-dimensional, advection-dispersion, mass transport, deterministic model. Advective transport follows the mean flow. Dispersive transport is proportional to the concentration gradient according to Fick's Second Law. The model is applicable to well-mixed dendritic streams. Reaches are divided into completely mixed sub-reaches. DoSag is site specific to Georgia, including terms for soil types common in the major physiographic regions in Georgia. The calibration, validation, and use of DoSag has never been published in a peer reviewed journal. Sensitivity analysis concerning DoSag has also never been published in a peer reviewed journal. There is no documentation that accompanies the model.

### Description of the Little River Experimental Watershed

The site selected for an investigation into modeling the levels of DO in the coastal plain of Georgia was the Little River Experimental Watershed (LREW) located in the Suwannee River Basin (Figure 2). It is one of six regional USDA research watersheds and is considered typical for the coastal plain area (Sheridan and Ferreira, 1992). The LREW is a subwatershed of the USGS eight digit hydrologic unit (HUC) 03110204, similarly named the Little River Watershed. The LREW occupies 334 km<sup>2</sup> in three counties: Tift, Turner, and Worth (Sheridan and Ferreira, 1992). Stream channel slopes vary between 1.0 and 3.69 m km<sup>-1</sup> (Sheridan and Ferreira, 1992). Streamflow is frequently low and may go to zero. Data from a weir at gauging station B in the LREW shows no-flow conditions occurring regularly in 2001 and 2002 but not 2003 (Figure 3).

The LREW is located in the Tifton Upland ecoregion (EPA website, 2004). This is a sub-category of the larger Gulf-Atlantic coastal plain physiographic region. Ecoregions are defined by similar soils, geology, and landuse. The Tifton Upland ecoregion occupies about 52,000 km<sup>2</sup>. The following description of the Tifton Upland comes from the EPA's (2004) ecoregion classification: "The Tifton Upland of Georgia has . . . a mosaic of agriculture, pasture, and some mixed pine/hardwood forests. Soils

# Gauging Stations in the LREW

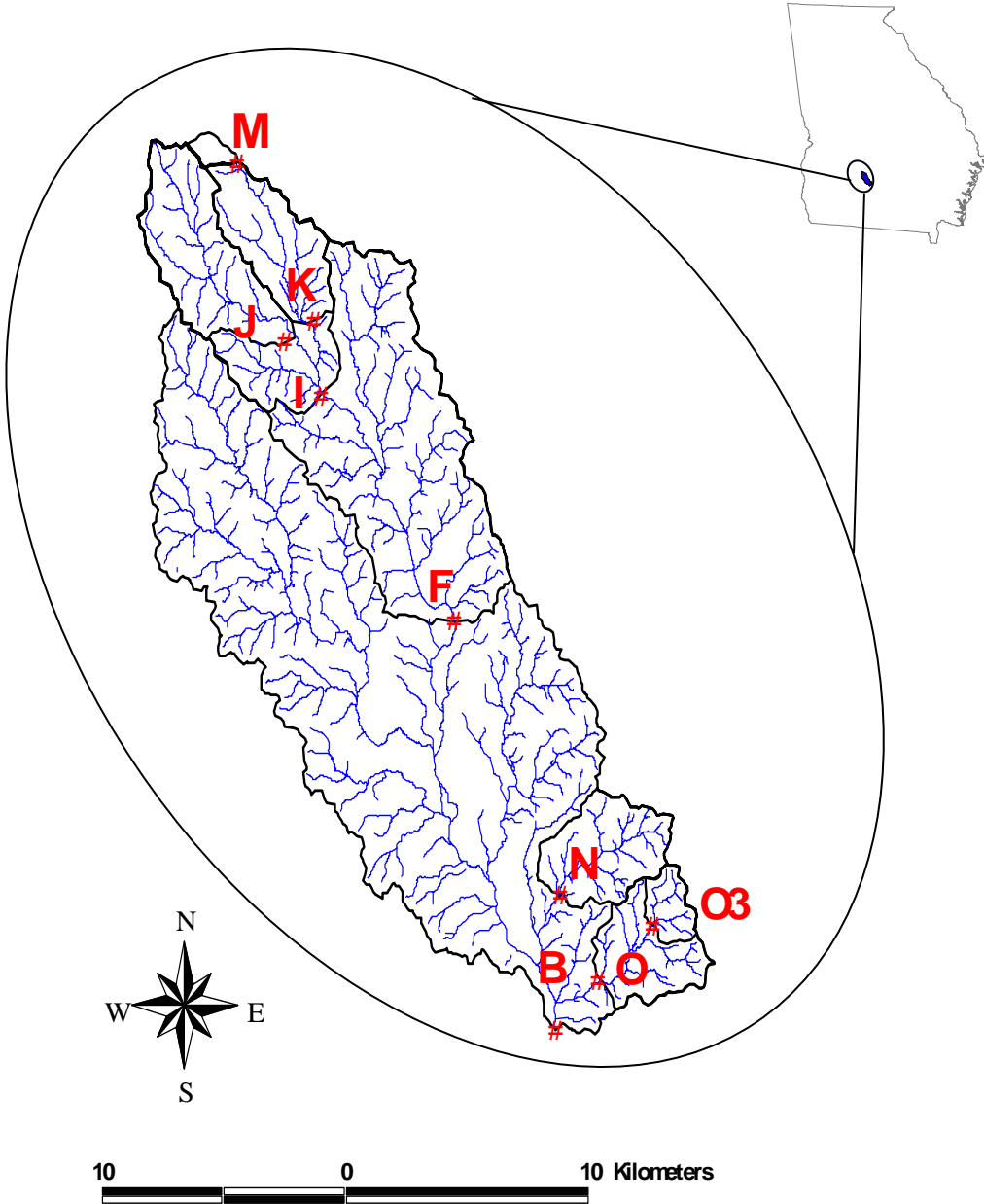


Figure 2. The Little River Experimental Watershed and gauging stations

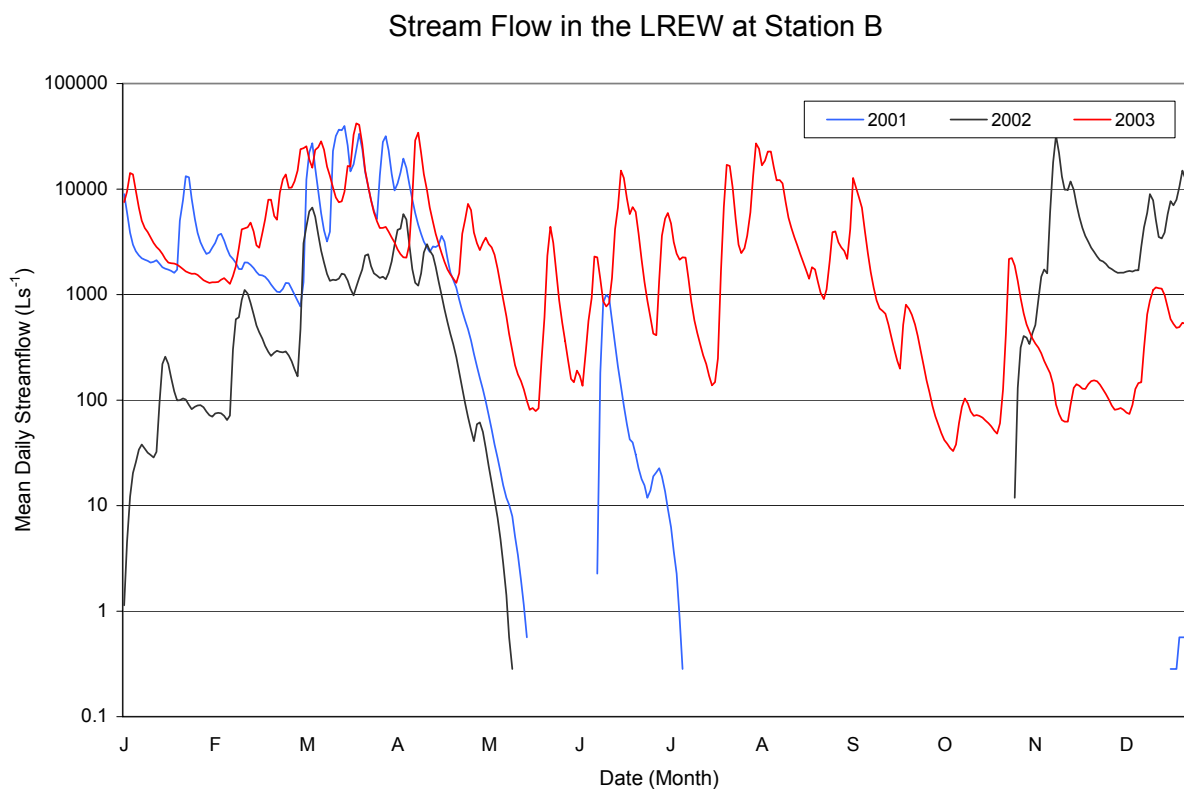


Figure 3. Streamflow at station B in 2001, 2002, and 2003. Note that flow goes to zero in two of the three years.

are well-drained, brownish, and loamy, often with iron-rich or plinthic layers. They support crops of cotton, peanuts, soybeans, and corn.” The Tifton Upland has a humid subtropical climate and experiences a mean annual precipitation of 119 – 142 cm per year. The area is topographically characterized by extensive floodplains and shallow slopes. Valley bottoms are flat and valley slopes exhibit gradients of less than five percent. Stream channels exist but can only be identified during low flow conditions because of their swampy nature. When streamflow is moderate to high, water is spread out over a broad, flat, wooded floodplain. When streamflow is low, water is confined to

the channels which are often braided. The Tifton Upland was typified by longleaf pine and wiregrass ecology before man settled the area. Little of the native ecology remains. Forestry and agriculture now dominate the area's landuse.

Streams in this area are termed blackwater streams because of their high concentration of humic substances. Humic substances come from the decomposition of organic material. Humic acids are intermediate colloidal products of decomposition. Tannins are soluble products that come from the further decomposition of humin. The sandy soils that characterize the coastal plain allow these humic substances to leach from the soil into the streams. Bodies of water with high concentrations of humic acids appear to be stained a dark coffee color and may have a low pH.

#### Description of historical data

The LREW was instrumented by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Southeast Watershed Research Laboratory (SEWRL) for hydrologic monitoring between 1967 and 1971. The SEWRL subdivided the LREW into eight nested watersheds, which have horizontal broad crested weirs with v-notched centers at each of their outlets. At each of these weirs streamflow is measured automatically with stage recorders every fifteen minutes. Rating curves, developed by SEWRL were used to convert stream depth to flow. The stations were periodically resurveyed and, if necessary, the equations were reworked to accurately represent flow. Figure 2 displays the locations of these gauging stations. Continuous monitoring of water quality has been conducted by SEWRL since 1991. A multi-parameter water quality SONDE was used to measure temperature, conductivity, pH, oxygen reduction potential, turbidity, and DO weekly. SEWRL also examined

biweekly grab samples for chlorophyll a, and fecal bacteria. Weekly samples of flow proportional composite water samples were analyzed for  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ ,  $\text{NO}_2\text{-N}$ , TN,  $\text{PO}_4\text{-P}$ , TP, and Cl by the University of Georgia. Stations B, N, and O have permanent dissolved oxygen meters that take DO and temperature readings every fifteen minutes. This continuous water quality dataset is supplemented by numerous intermittent samples collected since 1967. Station  $\text{O}_3$  has recently been introduced as the ninth subwatershed in the LREW. It is the only station that does not collect flow data. Because of the abundant data collected by SEWRL, the LREW has been chosen as the site for calibration and validation of DoSag.

## Chapter 3: Parameter Estimation

### Dissolved oxygen sinks and sources

DO is removed from a body of water through respiration, biochemical oxygen demand (BOD), and sediment oxygen demand (SOD). BOD is subdivided into two categories: carbonaceous biochemical oxygen demand (CBOD) and nitrogenous biochemical oxygen demand (NBOD). CBOD is the oxygen demand created by microorganisms that get their energy from oxidizing organic carbon. NBOD is the oxygen demand created by microorganisms that get their energy from oxidizing nitrogen. Pollutants which cause CBOD and NBOD may enter a stream through point or nonpoint sources. At the time the research was conducted, there were no listed NPDES permitted point sources in the LREW. SOD is the oxygen demand that is exerted by various chemical, biochemical, and biological processes that occur in the sediments.

DO is brought into a volume of stream water through reaeration and photosynthesis. Reaeration is the physical flux of oxygen between air and water. DoSag allows the user to choose between three methods for calculating reaeration rates: direct input, the O'Connor Dobbins (1958) equation, and the Tsvoglou equation (1976). Photosynthesis refers to the addition of DO to a body of water by photosynthesizing organisms. Photosynthetic oxygenation is input as a constant that is

equal to the net value of photosynthesis minus respiration. The BOD that is exerted by the decay of these photosynthesizing organisms is a sink that is calculated as a part of the total BOD.

### The dissolved oxygen sag curve

The DO sag curve represents how the DO concentration in a volume of water changes over time or distance after organic material is introduced. This curve is calculated by the Streeter-Phelps equation. All in-stream DO models, including DoSag, are based on the concept of the dissolved oxygen sag curve (Figure 4) and the Streeter-Phelps Equation. When a biochemical oxygen demanding substance such as sewage enters a river, the organic material provides a source of energy for decomposer microorganisms living in the water. This energy surplus leads to population growth in the decomposers. These aerobic decomposer microorganisms consume dissolved oxygen through respiration. As their population increases, they consume more organic material and more oxygen. The population begins to die off at some point because the organic material is depleted and their energy becomes limiting. Theoretically, the microorganisms continue to die off until there are no oxygen-demanding substances left. As oxygen is being used up by the decomposers, the river is also reaerated by the physical flux of oxygen from the air into the water. When the oxygen demand is less than the reaeration rate, the concentration of DO increases until it reaches atmospheric equilibrium. When the oxygen demand is greater than the reaeration rate, the concentration of DO decreases. This changing concentration of DO in a river after the introduction of organic material is called the DO sag curve.

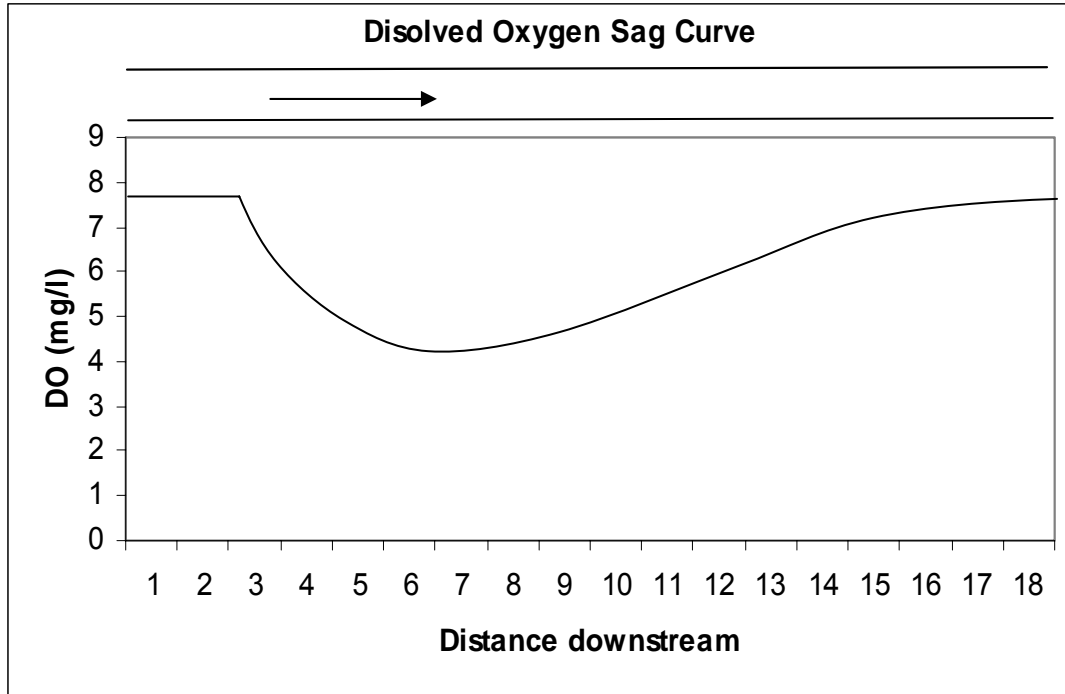


Figure 4. The dissolved oxygen sag curve.

The Streeter-Phelps equation

Various programs (WASP, QUAL2E, DoSag) have been developed to model DO in rivers. All of these models calculate DO using modified forms of the Streeter-Phelps equation (Streeter and Phelps, 1925) (Equation 1), which describes the DO sag curve. The original equation included terms for CBOD and reaeration only and stated that the DO deficit in a body of water was equal to the initial DO deficit plus reaeration minus deoxygenation from the BOD process.

Equation 1. The Streeter-Phelps equation.

$$D = D_0 e^{-k_a x/u} + \frac{k_d L_0}{k_a - k_d} (e^{-k_d x/u} - e^{-k_a x/u})$$

D = dissolved oxygen deficit (DO saturation minus the actual level of DO) (mg L<sup>-1</sup>)

D<sub>0</sub> = dissolved oxygen deficit at x = 0 (mg L<sup>-1</sup>)

k<sub>a</sub> = first-order reaeration rate coefficient (d<sup>-1</sup>)

x = distance (m)

u = average velocity (m s<sup>-1</sup>)

k<sub>d</sub> = first-order deoxygenation rate constant (d<sup>-1</sup>)

L<sub>0</sub> = CBOD (mg L<sup>-1</sup>)

There are several additional factors responsible for levels of DO in streams that were not included in the original Streeter-Phelps equation. Thomann and Mueller (1987) published a more comprehensive list of sources and sinks of DO that may be included as variables in the DO sag equation. The list includes: reaeration, DO from incoming tributaries, CBOD, NBOD, SOD, and respiration and photosynthesis by aquatic organisms. This list of sources and sinks will serve as a reference throughout this paper. Although the list is clear, the ways that these factors are mathematically incorporated into a model vary from model to model.

### DoSag model parameters

The DoSag model contains many parameters, rates, and coefficients that dictate the rates of DO sources and sinks and ultimately the DO, DoSag's state variable. The flow diagram shown in Figure 5 illustrates how various parameters and processes affect

DO in a stream reach. The blue boxes show the various sources and sinks of DO, the circles represent parameters that affect these processes, and the diamonds represent the locations where dissolved oxygen is held.

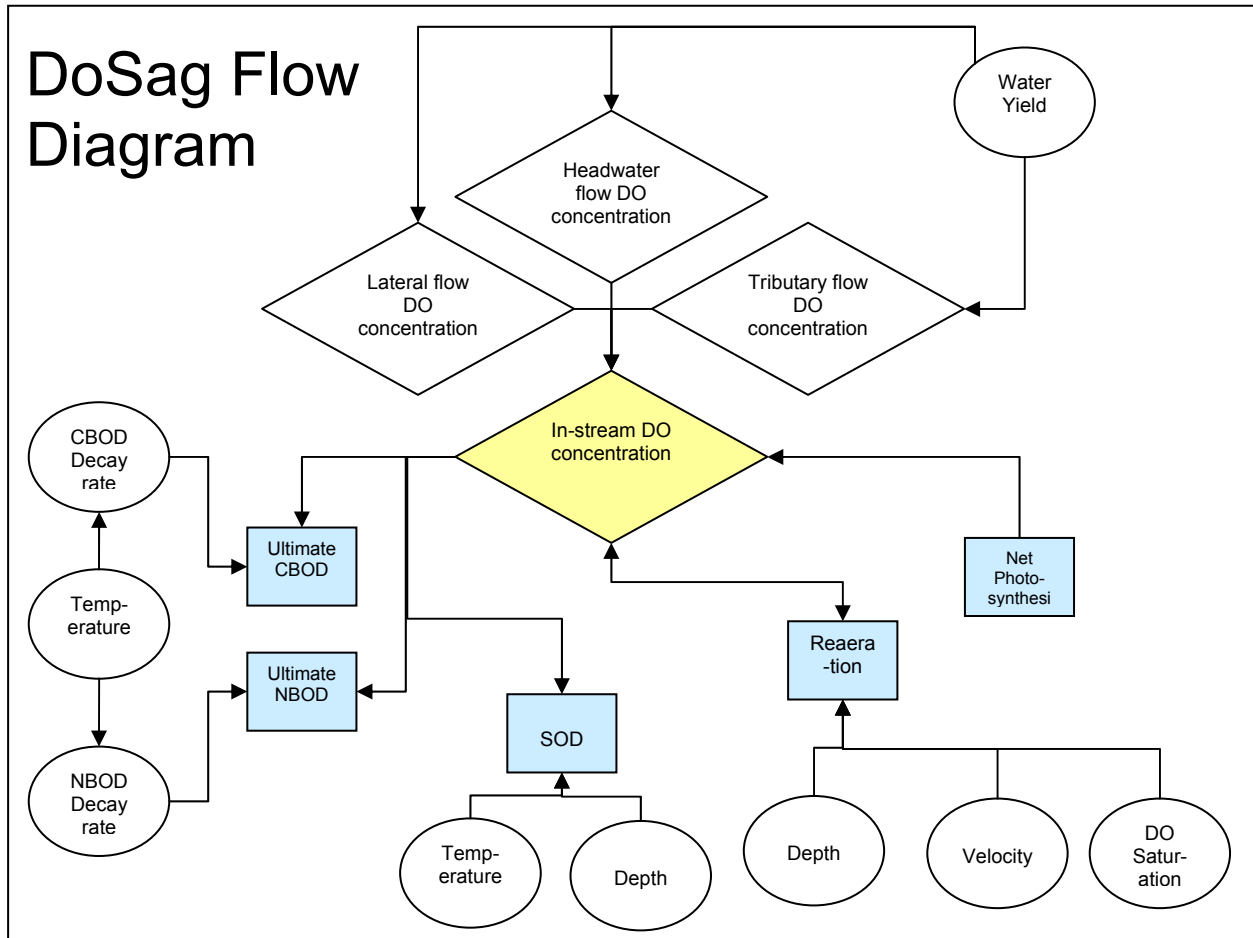


Figure 5. A flow diagram of the DoSag model.

QUAL2E is another in-stream water quality model and is perhaps the most widely used in-stream dissolved oxygen model today. The QUAL2E model is similar to DoSag, but makes use of more empirical equations and fewer parameter inputs. The net production of oxygen through photosynthesis is an example of this difference. The QUAL2E model calculates net photosynthesis from an equation based on chlorophyll *a*

concentrations and climatic variables. There are several variables in the QUAL2E model that can be manipulated within this chlorophyll equation but the user is not given a choice of which equation to use. However, DoSag asks the user to input a constant value for net photosynthesis per reach. It is up to the modeler to decide which equation, literature value, or tested measurement will be used to decide this value. This allows the user greater freedom. The quantification of BOD also reflects how DoSag is more influenced by parameter input than QUAL2E. The f-ratio converts five-day BOD (BOD that is exerted in a five day period) into ultimate BOD (the total BOD that can be exerted independent of time). QUAL2E asks the user for a five-day BOD. It has an internal f-ratio of 1.46 to convert five-day to ultimate BOD (BOD<sub>u</sub>). The f-ratio in the QUAL2E model is static and cannot be changed. On the other hand, DoSag asks the user for the ultimate BOD and the degradation rate of that BOD. These values are not internally calculated as they are in the QUAL2E model. The two examples illustrate how DoSag is much more of a parameter driven model than QUAL2E.

Because DoSag is so driven by parameter input, model input values must be chosen with care, in order to get appropriate model output. There are several ways that parameter values can be selected. Parameters can be based on literature references, calculated through equations, or directly measured. Parameters estimated for this research included temperature, flow, depth, velocity, channel slope, reach length, watershed area, reaeration, DO saturation, ultimate NBOD and CBOD, decomposition rate of NBOD and CBOD, SOD, photosynthesis, respiration, and the DO concentration of water flowing into each reach from tributaries and groundwater. The following paragraphs describe the methods used to decide upon a value for each of these

parameters. Many of these parameters vary seasonally. The values used were based on the date selected for calibration, March 12, 2004, whenever possible. Model calibration will be discussed in detail in the Calibration chapter.

### Dissolved oxygen

The state variable, DO was measured by SEWRL and The University of Georgia at eight and sometimes nine sampling stations in the LREW. DO has been measured weekly since 1991 and intermittently since 1967. Measurements were taken with a Yellow Springs Instruments (YSI) DO instrument which electrochemically measures DO with a steady state polarographic sensor. The measurement is based on the relationship between an increasing current passing through the water and the increasing voltage used to produce the current. The sensor that was used has an accuracy of plus or minus two percent in air saturated water. The resolution of the sensor is  $0.1 \text{ mg L}^{-1}$

SEWRL installed permanent DO probes at gauging stations B, N, and O. These permanent probes took DO and temperature readings every fifteen minutes. This dataset is intermittent because the probes are removed during periods of zero flow to prevent sensor damage.

### Skeletonization

Physical parameters describing the topography and hydrology of a watershed play an important role in modeling DO in streams. A real stream network is generally a very large number of tributaries and branches. A model is a simplified representation of the real system. So, to model DO in the LREW, the real stream network was simplified and the DO processes were compartmentalized. Model skeletonization refers to the

process of simplifying a watershed by dividing it up into subwatersheds.

Subwatersheds contain either points of water input into a stream or lengths of stream reaches. Subwatersheds are classified as being either reaches, tributaries, or headwaters. A reach is a section or length of a stream that, for modeling purposes, is assumed uniform. A branch is a group of reaches that follow a linear downstream path. A mainstem is an example of a branch. A tributary is a subwatershed that enters a branch at some point. Tributaries do not contain a length on the branch, just a point of discharge into the branch. Headwaters are tributaries that are located at the uppermost point of a branch. DoSag further breaks up each reach into lumped parameter completely mixed computational reaches of constant length,  $\Delta x$ . DO processes are recalculated within each computational reach.

The LREW was skeletonized in ArcView (ESRI; Redlands, CA). USGS digital elevation maps and hydrologic datasets were used to delineate subwatersheds for the skeletonization of the model. A subwatershed outlet was defined at each of the gauging stations. ArcView was then used to calculate subwatershed areas, reach lengths, reach slopes, and the location of the gauging stations. Figure 6 shows the skeletonization of the watershed used for modeling. Locations of the sampling stations (M, K, J, I, F, N, O, O<sub>3</sub>, and B) are also included in this Figure. Data for each modeling reach were not collected. Rather, field data were only collected at the nine sampling locations. Figure 7 shows the numbered subbasins in the watershed. The subbasins will be referred to by these numbers throughout the paper.

## Skeletonization and Sampling Locations in the LREW

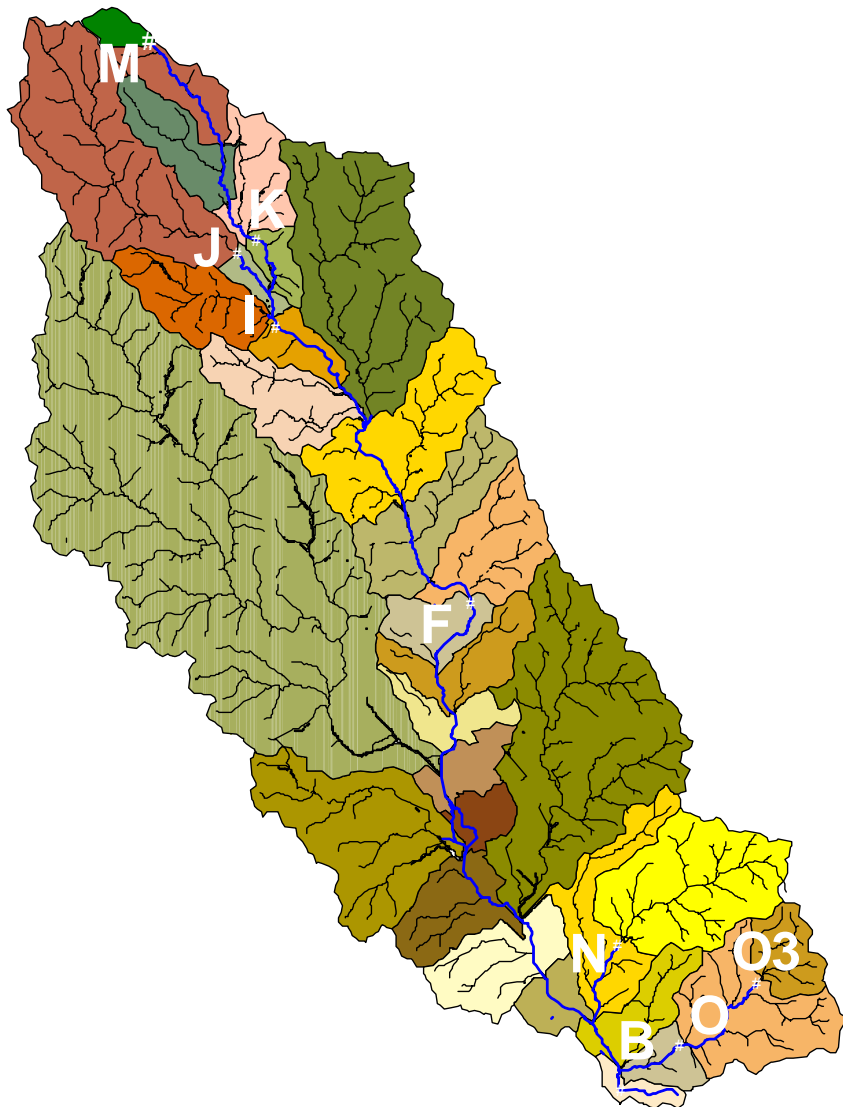


Figure 6. The skeletonization of the LREW.

# The LREW and Numbered Subbasins

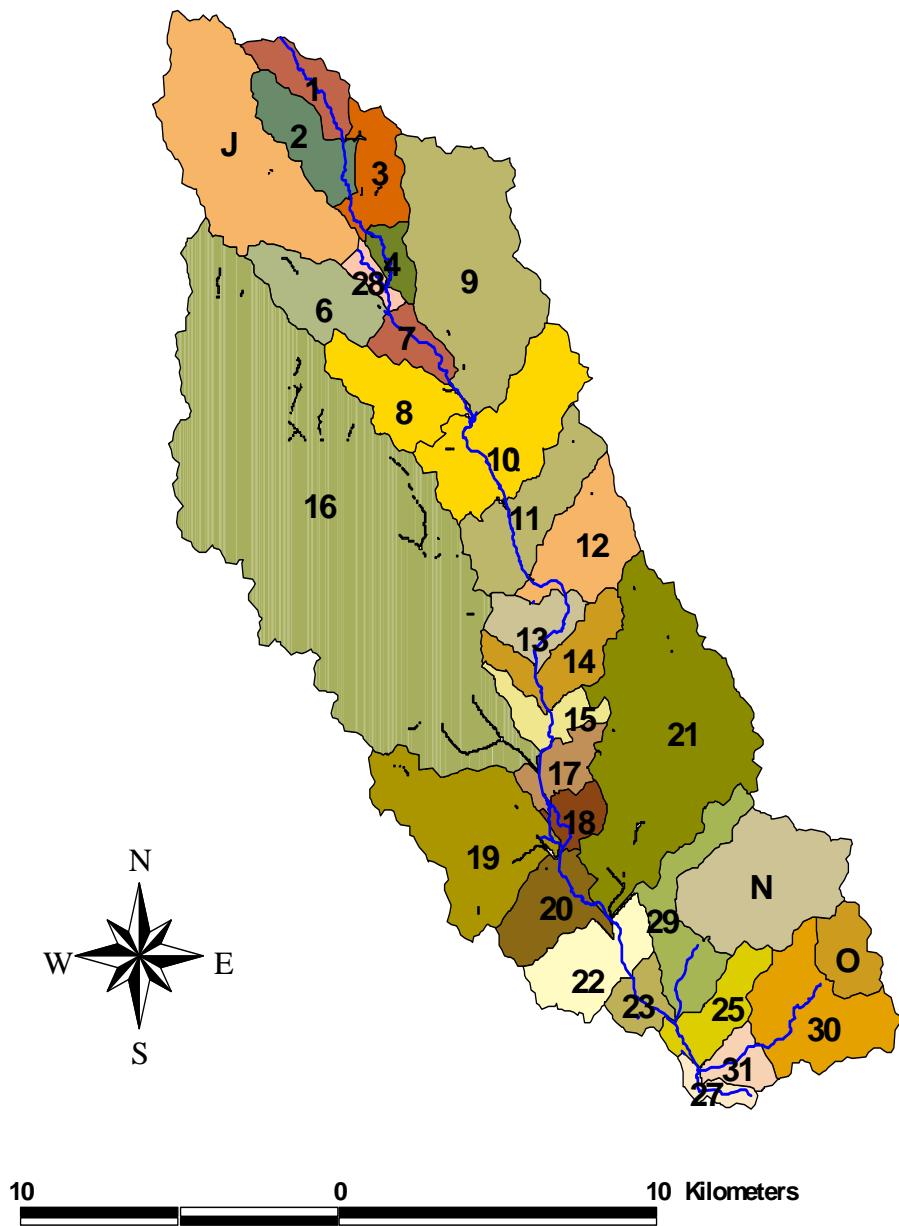


Figure 7. Numbered subbasins in the LREW.

The LREW watershed was divided into four branches: the main channel and branches J, N, and O. Each branch contained its own headwater. There were a total of 35 stream segments including: five tributaries, 23 stream reaches, four headwaters, and three branch junctions correlating to the J, N, and O gauging stations. A branch junction is the point at which one branch joins another. This is for the purposes of mixing. A branch junction does not have an area associated with it. All of these segments insert or delete DO from the system in different ways. Tributaries and headwaters import a load of oxygen and BOD. This load is mixed with the reach that is located immediately downstream. Reaches import a load of oxygen from the lateral flow and upstream flow that is input at the head of the reach. Reaches are where BOD, SOD, reaeration, and photosynthetic processes occur. These processes are not modeled in headwaters, tributaries, or branch junctions

Reaches were divided based on watershed topology, hydrology, and length. More watersheds and shorter stream reaches create a smoother model output because large amounts of lateral flow are not input into the top of each reach. However, more modeling reaches also means a more cumbersome model. A target length of approximately 1.5 km was used to define the reaches. This length was based on Dr. Roy Burke's (2004) recommendations as well as a balance between model smoothness and manageability. In the final skeletonization, stream reach length varied from 1.21 to 4.02 km. Most reaches were approximately 1.60 km long.

According to USGS digital elevation maps (DEMs), several of the stream reaches had zero slopes. This may have been a result of round off error. However, according to the DEM data, the slope in the last reach, just before the sampling station B, was

actually positive; the channel elevation increased approximately one meter in this direction. DoSag did not allow for the topography to increase in the downstream direction because theoretically it would halt flow. Therefore, a slope of zero was chosen for this reach.

### Flow

Flow is important in the DoSag model because it is the medium in which DO is dissolved. Each of the nine sampling stations in the LREW except for station O<sub>3</sub> contained a weir and stage recorder. Flow was automatically calculated from the stage data using rating curves developed by SEWRL. Daily average flow was then calculated from the fifteen minute readings at each sampling station for each modeling day.

Daily average flow was calculated for March 12, 2004, the calibration date. Starting at the headwater and going to the end of the main channel: flow at station M was 15 L s<sup>-1</sup>, flow at station K was 181 L s<sup>-1</sup>, flow at station I was 217 L s<sup>-1</sup>, flow at station F was 560 L s<sup>-1</sup>, and flow at station B was 1400 L s<sup>-1</sup>. As would be expected, flow increased in the downstream direction. The only exception to this was at station I. Stations J and K measure flow from two branches which meet to form the stream gauged at station I. On the calibration date, the combined flow from stations J and K was greater than the flow downstream at station I. This means that flow decreased between the junction of stations J and K and station I. The downstream decrease in flow may have been due to the fact that on the calibration date, March 12, 2004 it had not rained in almost two weeks. Bosch et al. (1996) noted that in coastal plain forested areas, during summer months, groundwater flow reversed direction. Because of increased evapotranspiration, the hydrologic gradient switched direction and flowed

away from streams and toward forested area. This may explain why the flow at station I was less than the combined flows at stations J and K. DoSag does allow for the user to input a negative flow value.

### Water yield

Streamflow enters a reach through headwaters, tributaries, and lateral flow. Each of these types of flows was considered during this research. Flows in the subwatersheds were calculated based on a water yield (Equation 2) defined as: streamflow divided by contributing watershed area. Average daily streamflow was calculated at each gauging station from stage data and rating curves. Subwatershed areas were calculated in ArcView. Flows in the headwaters and tributaries were calculated from the water yield per subwatershed. However, in the stream reaches, flow was the sum of the subwatershed water yield and the flow coming from the reach located directly upstream.

Equation 2. The general equation for water yield.

$$WY = \frac{Q}{A}$$

WY = Water yield ( $L s^{-1} km^{-2}$ )

Q = Flow out of the watershed ( $L s^{-1}$ )

A = Watershed area ( $km^2$ )

The calculation of the water yield was more complicated than Equation 2 because of the nested watershed configuration in the LREW. Flow measurements were

taken at eight weirs. Each weir measured flow from its total watershed area. A water yield had to be calculated for each of the stream segments based on data from the eight weirs. When calculating the water yield, flow values were proportioned among the stream reaches based on upstream and downstream flow data at the weirs. The flow measured at the upstream weir was subtracted from the flow measured at the downstream weir. The remaining flow was then divided among the reaches located between the two weirs based on subwatershed area. This allowed for a more accurate representation of flow. A water yield for each stream reach was calculated according to Equation 3. The choice of equation was based on the type of stream segment and the location of the segment relative to the gauging stations. On the calibration date, the water yield varied from -5 to 11 L s<sup>-1</sup> km<sup>-2</sup>. The negative value occurred at station I where the sum of the flows at stations K and J were greater than that at I.

Equation 3. Equations used to determine the water yield for each reach. The subscripts stand for the gauging stations and the titles indicate which stream reach used which equation.

M Headwater

$$WY = \frac{Q_M}{A_M}$$

J Headwater

$$WY = \frac{Q_J}{A_J}$$

N Headwater and segment 29

$$WY = \frac{Q_N}{A_N}$$

O Headwater and segments 30, 31

$$WY = \frac{Q_O}{A_O}$$

Segments 1, 2, 3

$$WY = \frac{(Q_I - Q_M)}{(A_I - A_M)}$$

Segments 4, 6

$$WY = \frac{(Q_I - Q_J)}{(A_I - A_J)}$$

Segments 7, 8, 9, 10, 11, 12

$$WY = \frac{(Q_F - Q_I)}{(A_F - A_I)}$$

Segments 13, 14, 15, 16, 17, 18, 19, 20, 22, 23, 25, 27

$$WY = \frac{(Q_B - Q_I - Q_N - Q_O)}{(A_B - A_I - A_N - A_O)}$$

### Stream cross-sections

Velocity and average depth are parameters that affect several sources and sinks of DO including: photosynthesis, reaeration, and SOD. Stream cross-sections were surveyed at each gauging station to estimate velocity and average stream depth (Appendix C). Traditionally, stream cross-sections are surveyed at bridge crossings for easy access and measurements. But, average depth and velocity at a bridge crossing

is not the same as it is in a natural channel. The confinement at the crossing deepens the channel and alters the velocity. Because of this artificial confinement, a representative natural cross section was selected and surveyed far enough upstream from each gauging station to avoid affects caused by the bridge crossing and weir. At least twenty depth measurements were made at each cross-section. Cross-sections varied between sampling stations especially with respect to width. Cross-sections located in the upper reaches were fairly channelized while cross-sections toward the end of the mainstem resembled swamps more than streams. For example, the width of the stream at station M was 2 m, and downstream at station K the width was 5 m. Further downstream, at station F the width was 39 m and at station B the width was 182 m.

The cross-section at station K was measured twice: once on March 19, 2004 and once on May 12, 2004 (Appendix C). One of the purposes of this exercise was to confirm that the cross-section did not change in the two months. A visual inspection of the two cross-sections showed that station K's bathymetry remained stable over the two month period.

It was initially assumed that each cross-section remained uniform between gauging stations, where another cross-section was taken. Details of this assumption and the changes made to it are described in the Calibration chapter.

### Water depth

Average water depth was calculated from the surveyed cross-sections. But, average depth is not static, rather it changes when flow changes. This change was accounted for by adjusting the cross-sections according to the stage data. The streams

were surveyed from bank top to bank top. So, stream banks were surveyed as well as underwater depths and water levels. On each survey day, a mass balance was assumed such that the water level and flow at the weir was equal to the water level and flow at the location of the corresponding cross-section. Stage datum was recorded at the time that each cross-section was taken. For each scenario and gauging station, the cross sections were drawn in AutoCad. Depth was then adjusted in AutoCad by raising or lowering the water line according to the stage data on the modeling day. Average depth for a particular flow was then recalculated. When the channel cross-sections were recalculated based on stage data for March 12, 2004, average depth throughout the watershed only varied between 0.27 and 0.58 m.

### Velocity

Streamflow was known from the stage data and rating curves. The cross-sectional areas were recalculated in AutoCad for each modeling day to obtain average depth. Average velocity at each gauging station was then calculated using the continuity equation (Equation 4).

Equation 4. The continuity equation.

$$Q = VA$$

Q = flow ( $\text{m}^3 \text{s}^{-1}$ )

V = velocity ( $\text{m} \text{s}^{-1}$ )

A = area ( $\text{m}^2$ )

Average velocities on the calibration date varied between 0.018 and 0.152 m s<sup>-1</sup> (except at station K). The slower moving waters occurred at stations F and B which were also the areas with the widest cross-sections. The swifter moving waters occurred in the upper reaches around stations M, J, N, and O. The calculated velocity at station K was unusually high (0.54 m s<sup>-1</sup>). A resurvey of the cross-section at station K was conducted to rule out the possibility of errors in measurement.

#### Water temperature

Weekly temperature measurements at the nine gauging stations have been collected intermittently since 1967 and weekly since 1991. On the calibration date temperatures were fairly cool and varied minimally. On March 12, 2004, the maximum sampled water temperature was 13.0°C and the minimum sampled temperature was 11.6°C. The temperature in each segment was assumed to be equal to that measured at the nearest downstream gauging station.

#### Dissolved oxygen saturation

DO saturated water is water that contains as much DO as it can hold in solution at atmospheric equilibrium and a given temperature, pressure, and salinity. There are two ways to refer to how close a body of water is to saturation; the percent saturation and the DO deficit. The percent saturation is the existing concentration of DO in the body of water divided by the potential DO saturation for the same body of water under the same conditions. The DO deficit is equal to the percent saturation subtracted from the potential saturation, at the same temperature and pressure. Both percent saturation and DO deficit are useful terms that are used in various equations.

There are several equations that are used to calculate DO saturation. DoSag offers the choice between using the American Public Health Association (APHA, 1985) or the American Society of Civil Engineers (ASCE, 1984) equation to calculate DO saturation based on temperature. The APHA equation (Equation 5) was used in all modeling simulations.

Equation 5. The APHA dissolved oxygen saturation equation.

$$\ln(o_{sf}) = -139.34411 + \frac{1.575701 \times 10^5}{T_a} - \frac{6.642308 \times 10^7}{T_a^2} + \frac{1.243800 \times 10^{10}}{T_a^3} - \frac{8.621949 \times 10^{11}}{T_a^4}$$

$o_{sf}$  = saturation concentration of DO at 1 atm in freshwater ( $\text{mg L}^{-1}$ )

$T_a$  = absolute water temperature (K)

As stated previously, DO saturation depends on salinity, pressure, and temperature. For this project, salinity was assumed constant because the LREW streams are all freshwater streams and not tidally influenced. Atmospheric pressure was also assumed spatially constant because of the relatively uniform elevation in the LREW. Elevation in the watershed ranged from 81 to 146 m above mean sea level. DoSag does not allow the user to directly manipulate the barometric pressure. Temperature does have a significant affect on DO saturation and is inversely proportional to the DO saturation (Figure 8); the warmer the water, the less oxygen it can hold at equilibrium. For example, water with zero salinity, at mean sea level, and 20°C can only hold 9  $\text{mg L}^{-1}$  of DO in solution. But, the same water at 10°C can hold almost 12  $\text{mg L}^{-1}$  of DO in solution.

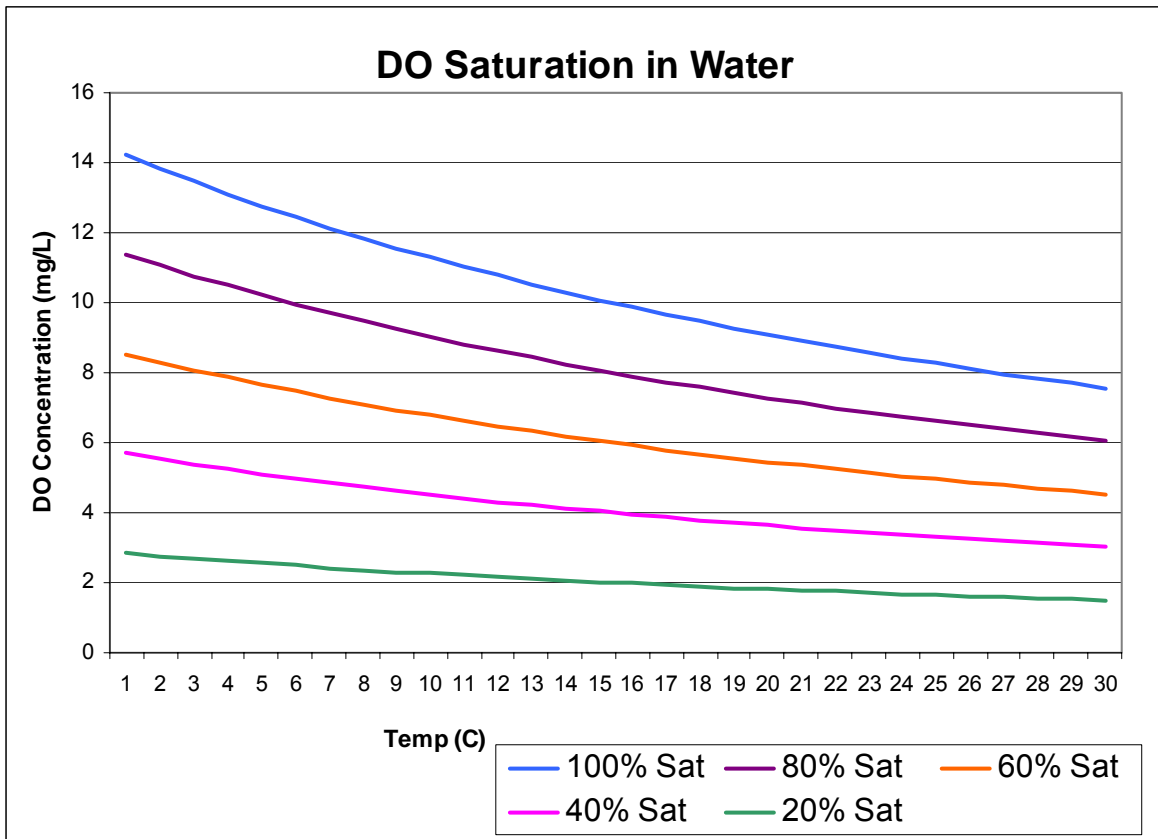


Figure 8. Dissolved oxygen saturation in water as it varies with temperature.

Figure 9 demonstrates the relationship between sampled DO, temperature, and percent saturation at station B in the LREW. The water temperature goes up in the summer; this trend is mirrored by decreasing DO concentrations.

Percent saturation may fluctuate throughout the system. DO may vary within the mainstem. Tributaries and headwaters may also have different levels of DO. Finally, the groundwater that feeds into the stream reaches also has its own DO concentration. The percent saturation of DO in each of these bodies of water should be considered when modeling the mixing of waters. DoSag simplifies this system and compartmentalizes DO into upstream, tributary, headwater, and lateral components.

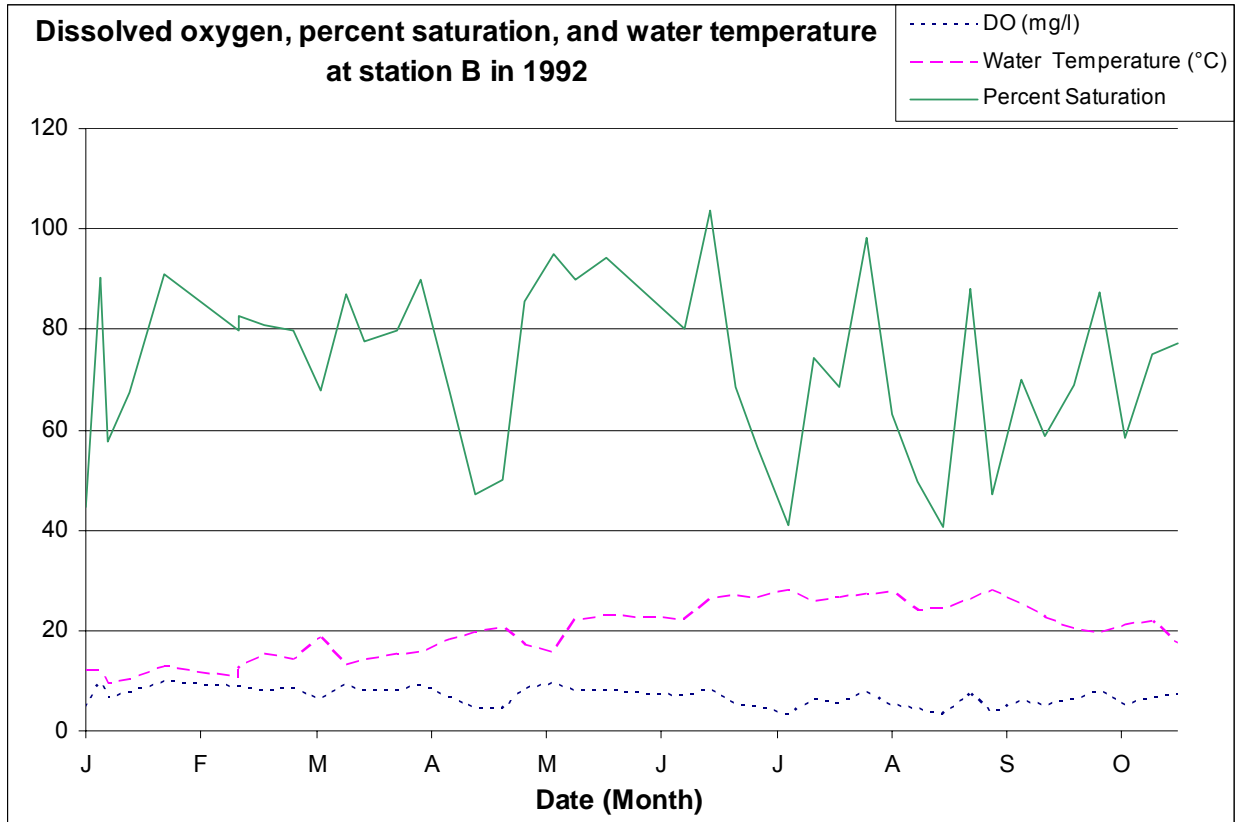


Figure 9. An example of annual fluctuations in dissolved oxygen, percent saturation, and temperature in the LREW.

Associated with each of these components is a DO concentration and flow rate. The upstream component refers to the water flowing into a reach directly from the nearest upstream reach. DO in upstream flow was calculated stepwise every 0.32 km by the Streeter-Phelps equation. Tributary and headwaters are point sources of DO and flow that are input by the modeler. For this research, the DO in tributary and headwater flow was assumed to be equal to that which was measured at the nearest downstream gauging station. Lateral flow is the additional flow which enters a reach between its inlet and its outlet. Lateral flow also has two components to it: the water entering a stream reach from tributaries that are not delineated in the model skeletonization, and the water

entering the reach from groundwater. DoSag lumps tributary and groundwater flow into one parameter termed lateral flow. Percent saturation for lateral flow is a user input and is not calculated by the model.

A modest investigation into the percent saturation of groundwater was conducted. The DO in groundwater was sampled in shallow groundwater wells (2 m deep) immediately adjacent to streams in the LREW. Wells were sampled at two sites, the University of Georgia dairy farm and the Gibbs farm. To measure percent saturation, water was first pumped out of the wells. The wells were then allowed to recharge. This was done to ensure that the DO measurements were representative of water occupying the soil matrix and not the well casing. DO in the recharged groundwater wells was then measured. The wells were sampled on four dates during 2004. DO in these wells was anoxic ( $0 \text{ mg L}^{-1} < \text{DO} < 1 \text{ mg L}^{-1}$ ) to hypoxic ( $1 \text{ mg L}^{-1} < \text{DO} < 5 \text{ mg L}^{-1}$ ) ranging from 0.19 to 3.72  $\text{mg L}^{-1}$ . Table 1 shows each measurement of groundwater DO in the LREW.

The percent saturation of DO from undelineated tributaries was also considered. If steady state conditions are assumed, then the DO in undeliniated tributaries is the same as the DO measured at the gauging stations. So, it was assumed that the DO from these undeliniated tributaries had the same DO concentration as water at the nearest downstream gauging station on the same day. This was the same assumption made about delineated tributaries.

To get the overall percent saturation of DO in lateral flow, the DO from groundwater and tributary flows were averaged. The infinite number of tributaries in the real watershed was simplified for the purposes of modeling. Most reaches, tributaries

Table 1. Sampled dissolved oxygen in groundwater wells.

<b>Date</b>	<b>Site</b>	<b>Groundwater DO (mg L<sup>-1</sup>)</b>
<b>4/29/04</b>	Gibbs Farm- uphill	0.40
	Gibbs Farm - downhill	0.59
	Dairy Farm - uphill	0.30
	Dairy Farm - downhill	0.94
<b>5/10/04</b>	Gibbs Farm - uphill	1.74
	Gibbs Farm - downhill	0.71
	Dairy Farm - uphill	0.19
	Dairy Farm - downhill	0.21
<b>5/23/04</b>	Gibbs Farm - uphill	3.72
	Gibbs Farm - downhill	1.37
	Dairy Farm - uphill	0.27
	Dairy Farm - downhill	0.19
<b>6-25-04</b>	Gibbs Farm - uphill	2.87
	Gibbs Farm - downhill	-----
	Dairy Farm - uphill	0.72
	Dairy Farm - downhill	0.48

and branches were ignored; only the mainstem and other significant stream segments were modeled (Figure 6). Groundwater only entered this simplified system from under the skeletonized reaches. The rest of the lateral and groundwater flow was associated

with undelinated segments. It was assumed that the DO concentration in these undelinated segments had already reached the level that was measured at the gauging stations. The flow rate of groundwater entering the streams was not measured. In the absence of measurements, it was assumed that 5 percent of the area in the LREW directly contributed to the skeletonized reaches through groundwater flow. Based on this assumption, an equation was created to average groundwater, and tributary inputs of dissolved oxygen. The number that was calculated by this equation approached the measured in-stream DO saturation (within  $0.25 \text{ mg L}^{-1}$ ). Because of this, and because of the arbitrary decision that 5 percent of flow would come directly from groundwater, the percent saturation from both groundwater sources and undelinated tributaries was assumed to be equal to the DO measured at the nearest downstream gauging station.

### Reaeration

Reaeration represents the physical flux of oxygen between the water surface and the atmosphere. The rate of reaeration is proportional to the DO deficit and a volumetric reaeration coefficient (O'Connor and Dobbins, 1958 and Churchill et al., 1962). The volumetric reaeration coefficient represents the rate that oxygen enters a body of water from the atmosphere. Depth, velocity, internal mixing, wind mixing, temperature, surface films, waterfalls, dams, and other physical obstacles affect the reaeration coefficient in streams (Thomann and Mueller, 1987).

There are many semi-empirical equations for calculating the reaeration coefficient. Variables that these equations may make use of include depth, velocity, time of travel, the gas escape coefficient, and the diffusivity of oxygen in water (Churchill et al., 1962; Owens et al., 1964; Tsvoglou and Neal 1976; Wilcock, 1988;

Krenkel and Novotny, 1980; and O'Connor and Dobbins, 1958). Reaeration may also be measured in-situ using gas tracer injections (Tsivoglou et al., 1968). DoSag gives the user three options for estimating the volumetric reaeration coefficient: the Tsivoglou equation (Equation 9) (Tsivoglou and Neal, 1976), the O'Connor Dobbins equation (Equation 11) (O'Connor and Dobbins, 1958), and direct input.

When either the Tsivoglou or the O'Connor Dobbins formula is used to calculate the reaeration coefficient, there are three equations that DoSag works through. First the reaeration coefficient is calculated according to either the Tsivoglou equation (Equation 9) or the O'Connor Dobbins equation (Equation 11). This coefficient is then temperature corrected according to Equation 6. Finally the amount of oxygen flux per volume and unit of time is calculated according to the general reaeration equation (Equation 7).

The Tsivoglou and O'Connor Dobbins equations were based on different sampling techniques and make use of different variables. Tsivoglou's equation (Tsivoglou and Neal, 1976) was derived from actual measurements of stream reaeration rates using a field tracer procedure. In their method, a radioactive form of the noble gas

Equation 6. The temperature correction for the volumetric reaeration coefficient.

$$k_{a-T} = k_{a-20} * 1.016^{(T-20)}$$

$k_{a-T}$  = the reaeration coefficient at temperature T

$k_{a-20}$  = the reaeration coefficient at 20°C

T = temperature in °C

Equation 7. The general reaeration equation.

$$D = D_0 e^{(-k_a t)}$$

D = the oxygen deficit at time = t (mg L<sup>-1</sup>)

D<sub>0</sub> = the initial oxygen deficit at time = 0 (mg L<sup>-1</sup>)

k<sub>a</sub> = the volumetric reaeration coefficient (d<sup>-1</sup>)

t = time (days)

krypton served as a tracer for oxygen. The experiments were conducted on several rivers with varying hydrologic characteristics. The average measured reaeration coefficient values in Tsivoglou's study ranged from 0.696 to 17.5 d<sup>-1</sup>. In the development of Tsivoglou's procedure, other reaeration rate formulas were compared with results obtained from the field tracer technique, but none appeared to predict stream reaeration rates as accurately as their model.

As shown in Equation 8, Tsivoglou's equation includes a term for the gas escape coefficient (c). Calibration results for sampled Iowa streams indicated that the gas escape coefficient should be selected based on the guidelines outlined in Equation 9. The gas escape coefficient decreases as streamflow increases.

The choice of the number used for the gas escape coefficient was based on an interpolation of the data shown in Equation 9 and streamflow in the LREW. Flows in the Little River Experimental Watershed rarely rose above 10000 L s<sup>-1</sup> at any station and often fell below 400 L s<sup>-1</sup>. Because this research is interested in modeling DO during critical DO conditions, most modeling scenarios occurred during low flow and low velocity scenarios. On the calibration date, the flow at station B, the end of the model,

was  $1400 \text{ L s}^{-1}$  and the flow at station M, the headwaters of the model, was  $150 \text{ L s}^{-1}$ . An average of these two flows was taken. This number was used to interpolate a reasonable number for the gas escape coefficient. The exercise resulted in value of 0.114, which was used to represent the gas escape coefficient under all flow conditions.

Equation 8. Tsivoglou's equation for reaeration.

$$K_2 = \frac{c\Delta H}{t}$$

$K_2$  = reaeration rate coefficient ( $\text{d}^{-1}$ )

$c$  = gas escape coefficient ( $\text{ft}^{-1}$ )

$\Delta H$  = change in water surface elevation (ft)

$t$  = time of travel (d)

Equation 9. The relationship between the gas escape coefficient and flow.

$$c = 0.054 \text{ (at } 20^\circ\text{C) for } 400 \leq Q \leq 85000 \text{ L s}^{-1}$$

$$c = 0.115 \text{ (at } 20^\circ\text{C) for } 0 \leq Q \leq 400 \text{ L s}^{-1}$$

The O'Connor Dobbins equation (O'Connor and Dobbins, 1956) is quite different from the Tsivoglou equation. Instead of being based on field samples, it was based on theoretical mechanisms and then verified in the laboratory and multiple field conditions. The equation assumes that "speed is directly proportional to the rate of surface renewal" (O'Connor and Dobbins, 1956). Unlike the Tsivoglou equation, the equation does not factor in slope. It is instead based only on depth, velocity, and the diffusivity of oxygen

in water. The O'Connor Dobbins assumes turbulent flow. The observed reaeration coefficients that were used to verify the equation varied between 0.018 and 5.3 d<sup>-1</sup>.

Equation 10. The O'Connor Dobbins reaeration equation.

$$K_a = \frac{D_l^{0.5} U^{0.5}}{H^{1.5}}$$

$k_a$  = reaeration rate coefficient (d<sup>-1</sup>)

$D_l$  = the diffusivity of oxygen in water (approximately 2.09X10<sup>-5</sup> cm<sup>2</sup> s<sup>-1</sup>)

$U$  = velocity (m s<sup>-1</sup>)

$H$  = water depth (m)

For this modeling project, the reaeration coefficient was calculated using the O'Connor Dobbins equation and not the Tsivoglou equation. The Tsivoglou equation depends on slope and time of travel within a reach. According to USGS digital elevation maps, slopes in several of the modeling reaches went to zero. As a result, the reaeration went to zero in these reaches when using the Tsivoglou equation. This lowered the overall reaeration for the stream network. The O'Connor Dobbins equation does not depend on slope and instead calculates the reaeration rate based on average velocity, depth, and the diffusivity of oxygen in water. If velocity goes to zero, the O'Connor Dobbins reaeration rate also goes to zero. However, the Streeter-Phelps equation (Equation 1) also depends on having a nonzero velocity. Because zero velocity conditions are impossible to model using the DoSag model anyway, the O'Connor Dobbins equation was used to calculate the reaeration coefficient. On the

calibration date, the temperature corrected reaeration rate varied between 1.6 and 8.58  $d^{-1}$  when using the O'Connor Dobbins equation.

Overall more reaeration occurred when the Dobbins O'Connor equation was used over the Tsivoglou equation. This increase was a result of higher overall numbers and also because there were no zero values. Reaeration rates computed by the O'Connor Dobbins equation ranged from 1.6 to 8.58  $d^{-1}$ . Reaeration rates using the Tsivoglou equation ranged from 0.3 to 6.3  $d^{-1}$  plus zero values in reaches with zero slopes.

### Biochemical oxygen demand

Biochemical oxygen demand (BOD) is the measurement of the consumption of oxygen by bacteria living in the water. Bacteria consume organic carbon and nitrogen. So, BOD in a stream increases with increasing amounts of organic material. There are two types of BOD that were measured for this project, carbonaceous biochemical oxygen demand (CBOD) and nitrogenous biochemical oxygen demand (NBOD). CBOD is exerted during the chemical oxidation of organic carbon. NBOD is exerted during the oxidation of the various forms of nitrogen.

BOD can be exerted by point and nonpoint sources and also influenced by incoming water from tributaries. BOD may come from natural sources like leaf litter fall or anthropogenic sources like urban sanitary wastewater and agricultural runoff. At the time that this research was conducted, there were no listed NPDES point sources in the LREW, so only nonpoint sources were modeled.

In streams, biochemical oxygen demanding substances can either float in the water column, settle to the bottom, or be resuspended from the sediment. Bhargava

(1983) assumed that point source BOD is removed in two stages below a sewage outfall. Stage one is short (30-60 min) and takes out about 60% of the BOD. During this stage, coagulation takes place and bioflocculated material settles out. Stage two is slower and assumes that the material which does not settle out during stage one decomposes through the normal first order BOD decay process. Settling was not calculated as a part of this research because point sources were not modeled and because modeling was conducted during low flow conditions when the concentration of suspended solids in the stream network is relatively uniform. Oxygen demanding substances can also resuspend during periods of high flow. The DoSag model does not include a direct means for modeling the resuspension of BOD.

Four variables are usually considered when calculating BOD: the ultimate BOD, the five-day BOD, the decomposition rate coefficient  $k$ , and the water temperature. Ultimate BOD refers to the total amount of oxygen consumed after all of the BOD has been exerted and all of the organic material has been decomposed, independent of time. Five-day BOD refers to the amount of oxygen consumed after a five day period. The decomposition rate coefficient for  $k$  describes the rate at which BOD is exerted. Water temperature positively affects the rate of decomposition but does not affect the ultimate BOD.

#### Carbonaceous biochemical oxygen demand

CBOD is the oxygen demand created by microorganisms that get their energy from organic carbon and not from nitrogen. CBOD is a part of the total BOD. The equation for CBOD is a first order linear differential equation: meaning that its rate of loss is proportional to its concentration at any given time (Thomann and Mueller, 1987;

Chapra, 1997; Streeter and Phelps, 1925). Equation 11 models the degradation of CBOD.

Equation 11. The decay of CBOD over time or distance.

$$L = L_0 e^{-k_d x / u} = L_0 e^{-k_d t}$$

L = CBOD concentration (mg L<sup>-1</sup>)

L<sub>0</sub> = CBOD concentration at x = 0 (mg L<sup>-1</sup>)

k<sub>d</sub> = deoxygenation rate constant (d<sup>-1</sup>)

x = distance (m)

u = mean velocity (m d<sup>-1</sup>)

t = time (d<sup>-1</sup>)

CBOD may be measured using the five-day BOD test or the long-term BOD test. The five-day test is the standard method for measuring CBOD. It measures CBOD degradation over a five day period. The five-day BOD protocol is outlined in *Standard Methods for the Examination of Water and Wastewater, 20<sup>th</sup> ed.* (APHA, 1998). In the Cape Fear Basin, a blackwater watershed in North Carolina, five-day CBOD was found to be approximately 1.0 mg L<sup>-1</sup> (McIver et al., 1999) and demonstrated no seasonal trend. The ultimate CBOD may be estimated from a five-day test using an f-ratio. The f-ratio is the ratio of the ultimate BOD to the five-day BOD.

The Streeter-Phelps equation requires ultimate CBOD and its deoxygenation rate as input parameters. The ultimate CBOD and the deoxygenation rate can be directly

measured by conducting long-term BOD tests. The long-term BOD protocol is outlined by the EPD (1989) and in *Standard Methods for the Examination of Water and Wastewater*, 21<sup>st</sup> ed. (APHA, 2001). This test is relatively new and is only proposed in *Standard Methods for the Examination of Water and Wastewater* 21<sup>st</sup> ed. (APHA, 2000). Both five-day BOD and long-term BOD tests were conducted for this study.

#### Nitrogenous biochemical oxygen demand

NBOD is the oxygen demand created by the oxidation of the various forms of nitrogen. Nitrogenous compounds found in water include organic nitrogen, ammonia, ammonium, nitrite, and nitrate. In waters with a low pH, ammonia is predominately present in the form of the ammonium ion. At a temperature of 20°C and pH of 9.4, ammonia and ammonium are at equilibrium.

There are several ways to calculate ultimate NBOD. The first method is similar to the method used for calculating ultimate CBOD. Equation 12 gives the removal of DO due to nitrification by a first order differential equation. Traditionally, paired tests of nitrogen inhibited and non-nitrogen inhibited five-day BOD tests are run. The difference between the two tests is the five-day NBOD (APHA, 1998). The problem with this method is that nitrogen may not begin to exert an oxygen demand until the end of the five-day test. So, five-day tests may miss much of the NBOD.

The second method for calculating ultimate NBOD is stoichiometric. This method depends on two chemical reactions conducted by bacteria as they convert ammonia to nitrate. Equation 13 represents the reaction conducted by the *Nitrosomonas* genus as it oxidizes ammonia to nitrite. Equation 14 represents the reaction conducted by the *Nitrobacter* genus as it oxidizes nitrite into nitrate. When the two equations are added

together, a total of 4.57 g of oxygen are required to oxidize one gram of ammonia into nitrate. So, the second way of estimating ultimate NBOD involves measuring ammonia and multiplying it by the 4.57 grams of oxygen that are required to break it down into nitrate.

Equation 12. The removal of DO due to nitrification by a first order linear differential equation.

$$c = c_s - L_0^N [1 - \exp(-K_N t)]$$

$c$  = concentration of DO at time  $t$  ( $\text{mg L}^{-1}$ )

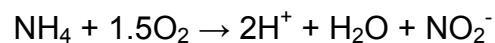
$c_s$  = initial concentration of DO ( $\text{mg L}^{-1}$ )

$L_0^N$  = initial concentration of NBOD ( $\text{mg L}^{-1}$ )

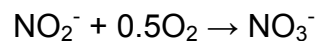
$K_N$  = overall oxidation rate of NBOD ( $\text{d}^{-1}$ )

$t$  = time ( $\text{d}^{-1}$ )

Equation 13. The chemical equation for the oxidation of ammonium.



Equation 14. The chemical equation for the oxidation of nitrite.



The third method for measuring NBOD involves the long-term BOD test. This method calculates the ultimate NBOD and its degradation rate,  $k_N$ . These two parameters are required for input into the DoSag model. Along with the long-term CBOD protocol, the long-term NBOD protocol is outlined by the EPD (1989) and proposed in *Standard Methods for the Examination of Water and Wastewater, 21<sup>st</sup> ed.* (APHA, 2001). In this method, the nitrate-nitrite and ammonia subsamples are periodically collected throughout the long-term BOD test. The aerobic evolution of nitrogen from ammonia to nitrite and then to nitrate in these samples indicates the NBOD of that nitrogen. The long-term BOD method was used to determine the NBOD of stream water for this modeling effort. This method was chosen over the others because the output from the test, ultimate NBOD and its oxidation rate, are inputs that are required in DoSag.

#### Five-day biochemical oxygen demand

Five-day BOD tests were performed to measure CBOD. The tests were conducted according to the method described in *Standard Methods for the Examination of Water and Wastewater 20<sup>th</sup> ed.* (APHA, 1998). The five-day BOD test is traditionally used by wastewater treatment facilities to standardize the measurement of the treatment of wastewater.

To determine the five-day BOD for this study, a sample of stream water was diluted. Three different dilutions were made for each sample site. Samples are traditionally diluted because undiluted samples of wastewater from treatment plants may contain enough BOD to deplete the oxygen concentration in a bottle to zero in five days; proper dilution ensures adequate residual DO. The term “seed” refers to a colony

of bacteria. After the water was diluted, the bottles were seeded to ensure that there was an active colony of bacteria in each bottle. The seed used for this project was wastewater treatment plant influent. Nutrients were also added to the bottles to support the bacteria. Nitrification was inhibited with 2-chloro-6 (trichlorometry) pyridine. The initial DO was measured using a YSI bench top dissolved oxygen sensor. Before testing began, the azide modification method 4500-0 C (APHA, 1998), commonly known as the Winkler method, was used to calibrate the DO probes to ensure that the automatic air calibration option on the DO meter worked properly. The probes were then automatically air calibrated before each use. YSI recommends air calibration over the Winkler method for the 5000, 5100 bench top DO sensors (YSI website, 2004).

After the dilutions were made, the samples were enclosed in airless and airtight 300 ml Wheaton DO bottles in a dark incubator at 20°C for five days. After five days, the DO was measured again and the oxygen depletion was calculated. Oxygen depletion caused by the seed was also calculated and subtracted from the total depletion. The oxygen demand was then multiplied by the dilution ratio to get the BOD of the pure stream water.

Seed controls, glucose-glutamic acid standards, and blanks were run along with the stream dilutions. Seed control bottles were run to calculate the oxygen consumption in the sample bottles by the addition of the seed. At least three seed control bottles were run for each five-day BOD test. Ingredients for the seed control bottles included deionized water, wastewater treatment influent, and nutrients. Each seed control bottle contained a different dilution of wastewater treatment plant influent. At least two standard bottles were also run with each five-day BOD test to ensure that the laboratory

method was working properly. A standard solution of glucose-glutamic acid was added to deionized water along with seed and nutrients. The glucose-glutamic acid had a known five-day BOD of  $198 \text{ mg L}^{-1}$  (plus or minus  $30.5 \text{ mg L}^{-1}$ ). The known BOD was compared to the sampled BOD to quantify the accuracy of the procedure. Blanks are bottles that were run with only deionized water. Two blanks were run with each test to ensure the cleanliness of the glassware. Ideally, the DO in a blank bottle should not change throughout the test. However, the standard method states that a depletion of  $0.2 \text{ mg L}^{-1}$  is acceptable for the blank bottles.

Samples were collected at all nine sampling locations on five different days during 2004. A total of forty five samples were processed along with standards, seed controls, and blanks. Results from the five-day BODs can be seen in Table 2.

The lower detection limit, for the five-day BOD test, established by *Standard Methods for the Examination of Water and Wastewater 20<sup>th</sup> ed.* (APHA, 1998) is  $2 \text{ mg L}^{-1}$ . Almost all of the results were below  $2 \text{ mg L}^{-1}$ . Some of the results were actually negative. A negative value is theoretically impossible. However, the BOD in the stream water was very low compared to the BOD in the wastewater treatment plant influent. Irregularities in the seed samples were probably the cause of these negative numbers. These low and negative values indicate that the standard five-day BOD test may not be appropriate for use in coastal plain stream waters with low BOD.

Figure 10 shows the averages of the five-day BOD tests in a spatial format. The data looks consistent throughout the watershed with the exception of stations O and O<sub>3</sub> where the levels of BOD were much higher. Within the watershed draining to station O<sub>3</sub> landuse is intensively agricultural with a high concentration of livestock. O<sub>3</sub> contains the

University of Georgia Tifton Campus Animal and Dairy Science Farm. This difference in landuse explains the high BOD measured at those sites.

Table 2. Five-day BOD results. Notice that some of the values are negative and almost all are below 2 mg L<sup>-1</sup>.

Site	Date				
	2/2/04	2/13/04	2/19/04	2/26/04	3/12/04
<b>M</b>	0.50	0.00	-0.20	0.73	1.10
<b>J</b>	1.19	0.15	0.26	0.38	0.88
<b>K</b>	1.11	0.36	0.55	0.85	0.99
<b>I</b>	1.33	-0.55	0.82	0.71	1.06
<b>F</b>	1.33	0.24	1.07	0.85	1.03
<b>B</b>	1.29	0.16	0.64	0.66	0.56
<b>N</b>	1.84	-0.83	0.47	1.37	0.80
<b>O<sub>3</sub></b>	1.54	2.13	0.89	4.38	1.23
<b>O</b>	3.06	1.24	0.78	2.11	1.23

## Average 5-day CBOD (mg/L) in the Little River Watershed

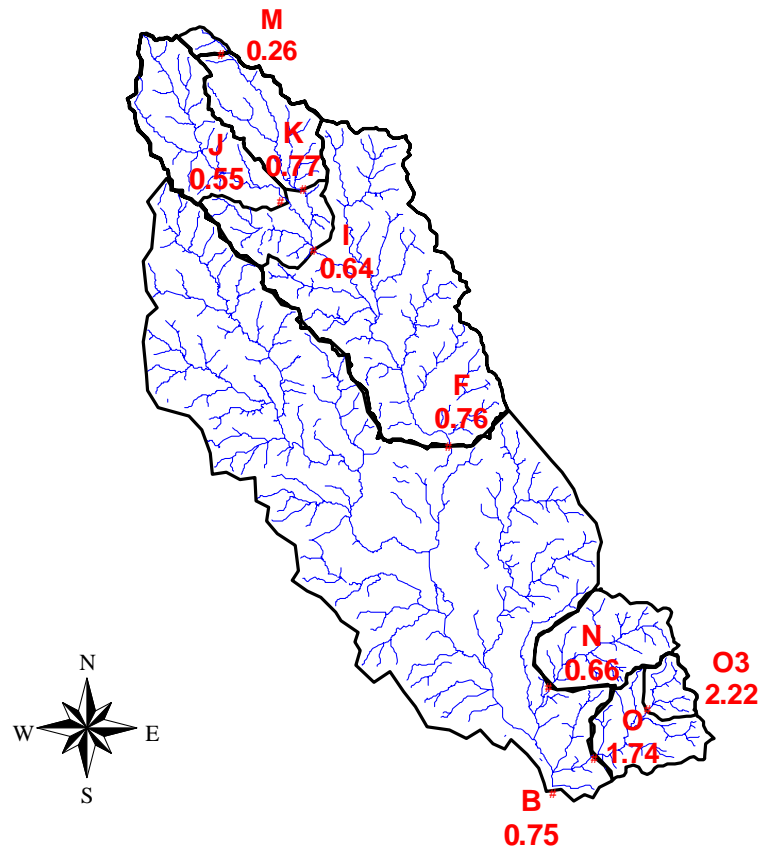


Figure 10. Average five-day CBOD in the LREW from samples collected from January to March 2004.

### Ultimate (long-term) biochemical oxygen demand

Long-term BOD tests were also conducted. The long-term test allows stream water to oxidize until there is no longer a significant oxygen demand exerted. The ultimate NBOD, CBOD, and associated degradation rates can all be calculated from the long-term test. The total amount of oxygen per unit volume consumed throughout the

test is the ultimate BOD. Testing nitrogen subsamples throughout the test yields ultimate NBOD. Ultimate CBOD is calculated by analyzing the nitrogen decay and total BOD data. The degradation rates for NBOD and CBOD are calculated by analyzing a graph of DO and nitrogen versus time.

The long-term BOD test is similar to the five-day BOD test. However, there are significant differences between the two tests. The long-term test takes 120 days instead of five. The extended length of time allows for almost all of the BOD to be exerted and the ultimate BOD to be calculated. The intermittent sampling of DO allowed the oxygenation rate to be calculated. The DO sampling schedule was designed to capture the BOD degradation curve, which would be steepest at the beginning of the test. Another difference between the two tests involves how the sample bottles were configured. Unlike the five-day BOD test, in the long-term test the stream water was unseeded and no nutrients were added. This was done because the seed and buffer additions may have accelerated decomposition and produced results that did not represent the natural decomposition occurring in the stream (APHA, 1998). The samples were also undiluted. This was done to mimic natural conditions in the streams. Furthermore, because of the length of the test, it was necessary to periodically reaerate the samples to avoid complete oxygen depletion. So, it was not necessary to dilute the stream water to avoid oxygen depletion as was done in the five-day test. Nitrogen inhibitors were not added to the bottles so that NBOD could be calculated. And finally, nitrogen subsamples were collected throughout the test to monitor the degradation of the various forms of nitrogen. Along with bottles of sample

stream water, one blank, one seed control, and two glucose-glutamine standard bottles were run for each sample date.

As stated above, the DO in the bottles was measured periodically throughout the test. In the first week, DO was measured every day. During weeks two and three, DO was measured every other day. In weeks four through six, DO was measured every third day. And finally, in weeks seven to eighteen, DO was measured every week. This schedule was adjusted for holidays, weekends, and other conflicts.

During the long-term test, if the DO in a bottle approached  $2 \text{ mg L}^{-1}$ , the sample was reaerated to ensure that the process of aerobic oxygen demand would continue. Reaeration was accomplished by emptying water into a large wide mouth container. The container was then placed on a stirrer and stirred at the highest level for about 10 minutes. DO was measured before and after reaeration.

To calculate NBOD, nitrogen subsamples were collected and analyzed throughout the long-term test. Eleven nitrate-nitrite and ammonia subsamples were collected periodically throughout the tests including collections on the first and last days of the tests. Nitrate-nitrite and ammonia concentrations were determined on a TRAACS 800 autoanalyzer at the University of Georgia's water quality laboratory in Tifton, Georgia. The nitrate-nitrite and ammonia methods are described in *Standard Methods for the Examination of Water and Wastewater 20<sup>th</sup> ed.* (APHA, 1998). Nitrate-nitrite was determined according to standard method 4500-NO<sub>3</sub>, the automated hydrazine reduction method. In the automated hydrazine reduction method, nitrate is reduced to nitrite and the nitrite concentration is measured colorimetrically. The detection limit for

this method is  $0.008 \text{ mg L}^{-1}$ . Nitrite-nitrate concentrations in the samples ranged from  $0.022$  to  $2.6 \text{ mg L}^{-1}$ .

The method used to determine the ammonia concentration was standard method 4500-NH<sub>3</sub>, the proposed flow injection analysis. It is also a colorometric method that measures both the ammonia and the ammonium cation. The addition of sodium phenoxide and sodium hypochlorite to ammonium results in a blue color. The intensity of the blue color correlates to the concentration of ammonia. No working range or detection limit was published in the 20<sup>th</sup> edition of *Standard Methods for the Examination of Water and Wastewater 20<sup>th</sup> ed.* (1998). Ammonia concentrations in the samples ranged from  $0.0001$  to  $1.2 \text{ mg L}^{-1}$ .

All nitrogen tests were run in duplicate. If the standard deviation between the duplicates was greater than five percent, the tests were rerun until the standard deviation fell below the five percent threshold. The results from the reruns were used if this occurred.

For each long-term test sample collection date, one seed control, one blank, and two glucose-glutamic acid bottles were run along with the stream samples. The seed control contained 100ml of wastewater treatment plant influent. The glucose-glutamic acid bottles contained 40ml of glucose-glutamic acid and 20ml of wastewater treatment plant influent each. The blank bottles contained only deionized water.

Long-term BOD samples were taken at five sampling locations on two different days April 26, 2004 and June 26, 2004. On the first date, the streams were not flowing. Samples for no flow conditions were collected at stations M, J, I, B, and O. On the

second date, the streams were under low flow conditions. Samples for flowing conditions were collected at sampling stations M, I, F, B, and O.

The long-term BOD program developed by Dr. Roy Burke (2004) was used to determine ultimate BODs from the DO measurements and the nitrogen subsamples. This program calculates CBOD<sub>u</sub>, NBOD<sub>u</sub>, CBOD<sub>k</sub>, and NBOD<sub>k</sub> by plotting the oxidation of the various forms of nitrogen and the change in DO in the bottle over time. NBOD was calculated using a logistics equation based on ammonia and nitrate-nitrite data. The NBOD curve was then subtracted from the total bottle BOD and the remaining BOD was considered CBOD. Finally, the CBOD curve was computed according to a first order differential equation. No NBOD analyses were run on blank, seed control, or glucose-glutamine bottles. An example of the curves that the program produced from the bottles of stream water is shown in Figure 11. An example of the curve and sampled data from the glucose-glutamine standard bottle is shown in Figure 12.

The results of all of the long-term BOD tests can be viewed in Table 3. Most of the data were similar. The only outlying values were at station M and K where the CBOD and the NBOD were both low. This may be explained by the fact that stations M and K are close together and at the beginning of the mainstem. Above station M is a swampy ponded area. This area may allow suspended solids to settle out of the stream water bringing down the BOD. Water in this area may also sit ponded for a long period of time, allowing most of the BOD to be exerted. These explanations, however, are only speculation. More data are required to come to an informed conclusion.

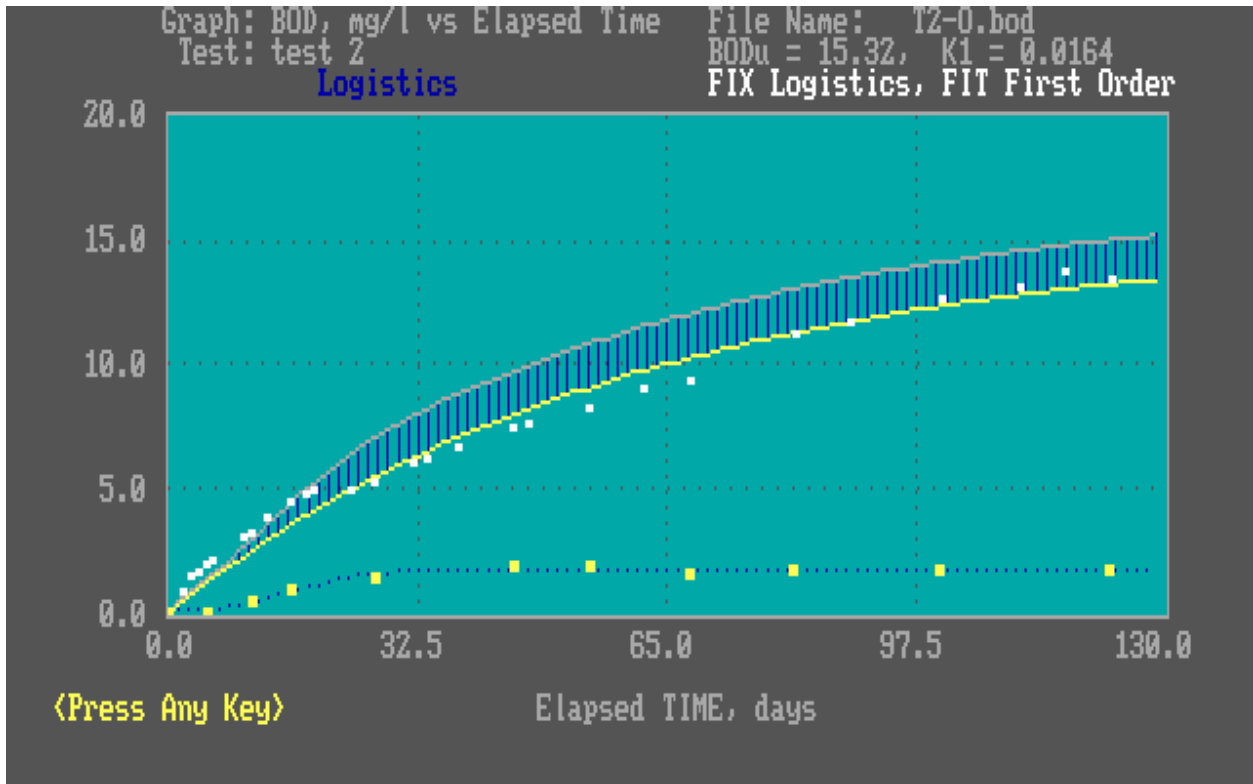


Figure 11. Long-term BOD program results from station O in the second test. The small white squares represent measured DO values. The large yellow squares represent measured NBOD. The yellow line represents CBOD using a first order differential equation fit. The blue dotted line represents NBOD values using a logistics fit.

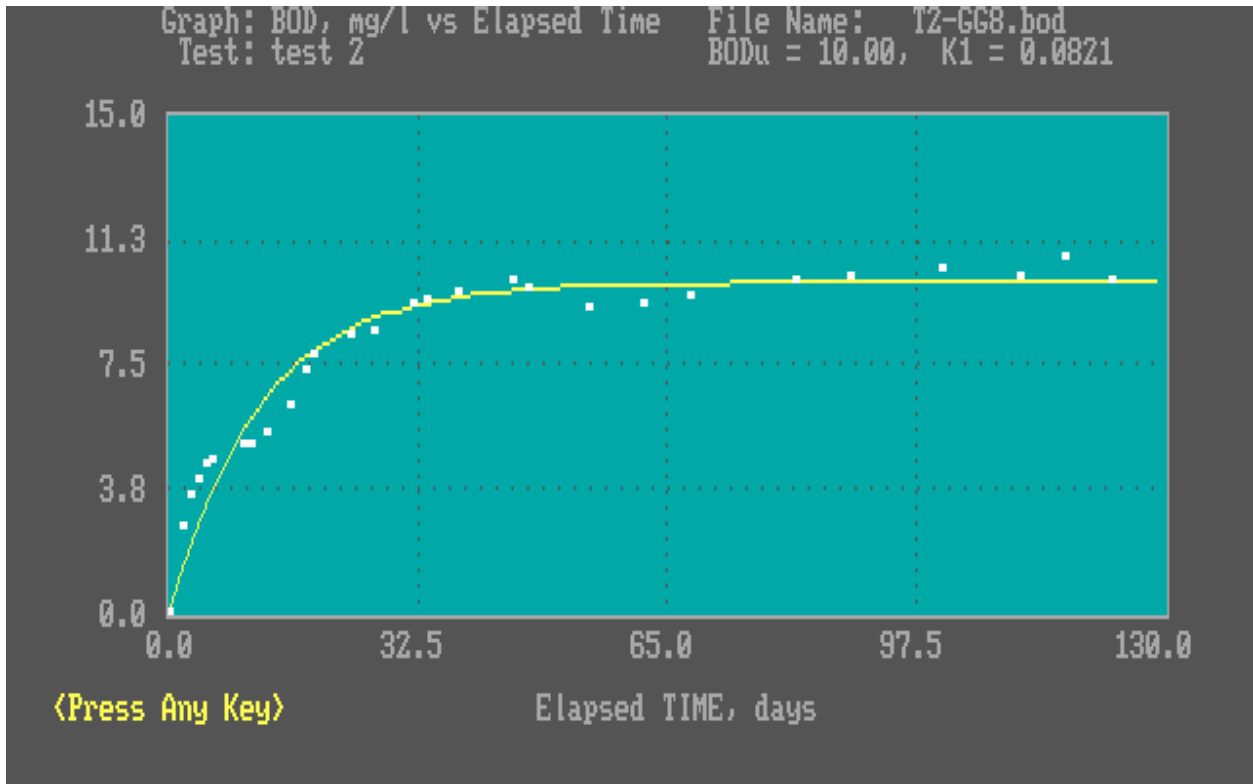


Figure 12. Long-term BOD program results from one of the glucose-glutamine bottles in the second test. The white squares represent measured DO values. The yellow line represents a first order differential equation fit.

Table 3. Blank corrected BOD values from the long-term BOD tests.

Test	Sample	CBOD <sub>u</sub> (mg L <sup>-1</sup> )	CBOD <sub>k</sub> (d <sup>-1</sup> )	NBOD <sub>u</sub> (mg L <sup>-1</sup> )	NBOD <sub>k</sub> (d <sup>-1</sup> )
<b>Test 1</b>  <b>(No Flow)</b>	Blank	Did not converge			
	Seed Control	10.63	0.723		
	Standard	8.24	0.085		
	Standard	8.26	0.081		
	<b>M</b>	<b>21.59</b>	<b>0.051</b>	<b>4.23</b>	<b>0.26</b>
	<b>K</b>	<b>7.12</b>	<b>0.048</b>	did not converge	
	<b>I</b>	<b>22.54</b>	<b>0.044</b>	<b>4.18</b>	<b>0.17</b>
	<b>B</b>	<b>16.43</b>	<b>0.043</b>	<b>2.97</b>	<b>0.12</b>
	<b>O</b>	<b>17.83</b>	<b>0.036</b>	<b>2.77</b>	<b>0.11</b>
<b>Test 2</b>  <b>(Low Flow)</b>	Blank	0	0.006		
	Seed Control	9.65	0.057		
	Standard	9.26	0.084		
	Standard	9.016	0.082		
	<b>M</b>	<b>7.95</b>	<b>0.031</b>	<b>0.60</b>	<b>0.08</b>
	<b>I</b>	<b>16.00</b>	<b>0.021</b>	<b>1.43</b>	<b>0.11</b>
	<b>F</b>	<b>14.78</b>	<b>0.019</b>	<b>1.32</b>	<b>0.19</b>
	<b>B</b>	<b>14.12</b>	<b>0.011</b>	<b>1.15</b>	<b>0.18</b>
	<b>O</b>	<b>14.33</b>	<b>0.016</b>	<b>1.77</b>	<b>0.20</b>

\* CBOD<sub>u</sub> refers to ultimate (long-term) CBOD

\* NBOD<sub>u</sub> refers to ultimate (long-term) NBOD

The blank bottles were used to measure the cleanliness of the glassware. The ultimate BOD for the blank bottle in the first test did not converge using either a first order or logistics equation. Therefore the blank bottle from the second test was used to correct for the ultimate CBOD in both the first and second test. This second blank bottle had a BOD of  $0.98 \text{ mg L}^{-1}$ , just below the  $1.0 \text{ mg L}^{-1}$  cited as the maximum blank BOD by the proposed standard method (APHA, 2000). According to the method, the BOD from the blank bottle was deleted from the other bottles before making any calculations.

The glucose-glutamine standard bottles were run to ensure that the test was properly conducted, that no toxins were in the samples, and that the seed was healthy. Glucose-glutamine has a known amount of oxygen demand. The assumption was that if the oxygen demand in the standard bottles matched the published values, then the test results could be trusted. According to the proposed standard method, a standard solution of glucose-glutamic acid should have an ultimate BOD between 308 and 321  $\text{mg L}^{-1}$ . These numbers were based on only 13 tests and should serve as guidelines not absolutes. After correcting for the blank bottle and the seed, the glucose-glutamine standard bottles showed an ultimate BOD of 305.9, 306.9, 366.8, and 354.3  $\text{mg L}^{-1}$ . The five-day BOD allows for an error of plus or minus 30.5  $\text{mg L}^{-1}$  from the stated standard of 198  $\text{mg L}^{-1}$ . That gives a total margin of error of 61  $\text{mg L}^{-1}$  of DO. The greater length of testing time and the reaeration of the samples in the long-term BOD test probably introduces additional error. Added to this is the fact that the long-term BOD method was only a proposed method and allowable errors had yet to be determined. Therefore, the values which were calculated from the long-term test were considered valid and used for modeling.

Samples for long-term BODs were collected twice, once during no-flow conditions and once during flowing conditions. The ultimate CBOD and NBOD results were consistently higher on the no-flow sample date than on the flowing sample date. The possible relationship between flow and BOD was investigated. Data from the five-day BODs were plotted to see if there was also a relationship between flow and BOD. This relationship was not detected in the five-day BODs. Because all modeling scenarios occurred during flowing conditions, the flowing long-term test was used as model input for ultimate NBOD, ultimate CBOD and their respective k values in each scenario. The long-term BOD dataset from the no-flow date was not used.

#### Photosynthesis and respiration

Aquatic respiration and photosynthesis take on various forms in rivers. Phytoplankton, periphyton, and attached and unattached aquatic plants all photosynthesize. Primary production can be a source or a sink of DO in streams. Algae respire, consuming oxygen, throughout the day and night. But, during the day, when there is a source of light, algae are able to photosynthesize and produce oxygen. Levels of DO may or may not reflect this diurnal shift (Gaush et al., 1998). According to Thomann and Mueller (1987), there are three ways of measuring oxygen production through photosynthesis in streams: light and dark bottles, the chlorophyll *a* equation, and the diurnal curve. Each of these methods was considered for this research and will be discussed in the following paragraphs.

#### Light and dark bottles

The light and dark bottle method was developed by Eugene Odum (1956). In this method, stream water containing phytoplankton is placed in a glass bottle. The

bottle is exposed to natural sunlight. The phytoplankton inside the bottle will photosynthesize and produce oxygen; at the same time the phytoplankton respire and use up oxygen. If the same bottle is covered and shielded from light then the phytoplankton inside will not be able to photosynthesize and will only respire. When using this method corrections must be made for BOD because, as the bottles sit, oxygen is consumed through the BOD process. The light and dark bottle method measures oxygen production from phytoplankton only. DO contributions from rooted aquatic plants or periphyton are not accounted for in this method.

The light and dark bottle method was not utilized for this project. Because of limitations of the Winkler method and experimental error, the method is not suitable for measurements on streams with chlorophyll concentrations less than  $1 \mu\text{g L}^{-1}$  (Vollenweider et al., 1969). Chlorophyll a levels in the LREW were frequently below this  $1\mu\text{g L}^{-1}$  threshold.

#### Chlorophyll "a" equation

A second method for calculating DO production through photosynthesis and respiration is the chlorophyll a equation (Equation 15) (Thomann and Mueller, 1987). This method is based on the concept 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. Chlorophyll a is a measure of the concentration of the pigment in green plants. So, it is an indirect indicator of phytoplankton biomass, and in turn, may be used as an indication of the oxygen production by that phytoplankton. But, because photosynthesis also depends on the presence of light and nutrients, the photosynthetic production of oxygen is also a factor of depth, solar radiation, the

extinction coefficient, and nutrients (Thomann and Mueller, 1987). One of the assumptions in this equation is that nutrients are not limiting. Carey's (2004) data show that in the coastal plain of Georgia nutrients are limited in some areas. However, most of these streams have a heavy canopy that shades the phytoplankton. In these shaded areas, light is the dominant limiting factor. As with the light and dark bottle method, the chlorophyll *a* method does not account for rooted aquatic plants or periphyton. The production of DO, by the chlorophyll *a* equation (Equation 15), was computed as a part of this research.

The chlorophyll *a* equation was paired with the respiration equation (Equation 16) (Thomann and Mueller, 1987) to calculate the net production of DO through photosynthesis and respiration. The respiration equation is based on the concentration of chlorophyll *a*, temperature, and a dimensionless stoichiometric ratio of oxygen to chlorophyll *a* produced. Since light is not a factor in respiration rates, variables such as the extinction coefficient, day length, and solar radiation were not considered in the respiration equation.

Grab samples of chlorophyll were collected biweekly at each monitoring station. The Southeast Watershed Research Laboratory of the USDA ARS in Tifton, Georgia analyzed the samples. The samples were processed according to the standard method 445.0, the in-vitro determination of chlorophyll *a* and pheophytin *a* in marine and freshwater, detailed in *Standard Methods for the Examination of Water and Wastewater 20<sup>th</sup> ed.* (APHA, 1998). The procedure measures chlorophyll *a* biomass through fluorescence. For this procedure, stream water was filtered through a glass fiber filter. The pigments were then extracted using acetone and a tissue grinder. Finally, the

slurry was centrifuged and the fluorescence was measured on a TD-700 flurometer.

The method's detection limit is  $0.11 \mu\text{g L}^{-1}$ .

Equation 15. The photosynthetic production of oxygen from chlorophyll *a* concentrations.

$$p_a = [a_{op} G_{\max} (1.066)^{T-20} P]G(I_a)$$

For:

$$G(I_a) = \frac{2.718f}{K_e H} [\exp(-\alpha_1) - \exp(-\alpha_0)]$$

$$\alpha_0 = \frac{I_a}{I_s}$$

$$\alpha_1 = \frac{I_a}{I_s} \exp(-K_e H)$$

$G(I_a)$  = dimensionless light attenuation factor over depth and one day

$I_s$  = the solar radiation at which phytoplankton grows at its maximum rate (langleys per day)

$I_a$  = average solar radiation during one day (langleys per day)

$K_e$  = extinction coefficient ( $\text{m}^{-1}$ )

$H$  = water depth (m)

$a_{op}$  = dimensionless stoichiometric ratio of oxygen production to chlorophyll *a* production

$G_{\max}$  = maximum phytoplankton growth rate ( $\text{d}^{-1}$ )

$P$  = chlorophyll concentration ( $\mu\text{g L}^{-1}$ )

T = water temperature (°C)

$p_a$  = gross oxygen production through photosynthesis ( $\text{mg L}^{-1} \text{d}^{-1}$ )

f = dimensionless f-ratio - CBODU/CBOD5

Equation 16. Respiration and oxygen depletion by photosynthesizing plants from chlorophyll a concentrations.

$$R = a_{op} (0.1)(1.08)^{T-20} P$$

R = phytoplankton respiration rate ( $\text{mg L}^{-1} \text{d}^{-1}$ )

$a_{op}$  = dimensionless stoichiometric ratio of oxygen to chlorophyll a produced

P = chlorophyll concentration ( $\mu\text{g L}^{-1}$ )

T = water temperature (°C)

Solar radiation data were collected for input into the chlorophyll a equation. The values that were used were measured by the Georgia Automated Environmental Monitoring Network Station in Tifton, Georgia. The solar radiation values do not account for shading by the tree canopy. But, streams in the coastal plain are shaded by riparian trees. For the purposes of this project, it was assumed that the canopy blocked fifty percent of the solar radiation. This assumption was based on radiation measurements made by Carey (2004) in April and March of 2004 in the coastal plain. Carey's measured ratio of shade to sun was 0.09. So, the canopy blocked out almost ninety percent of the total solar radiation. These measurements, paired with the best guess that about forty percent of these streams were under heavy canopy, led to the assumption that the streams received fifty percent of the total radiation.

An investigation into the affect that the seasonal variation of the tree canopy had on net photosynthetic production of oxygen was also undertaken. In the summer, when Carey (2004) collected solar radiation data, the leaves were on the trees and the canopy was full. However, in the winter, when deciduous trees loose their leaves, more solar radiation is able to reach the streams. Riparian areas in South Georgia are comprised of a mix of mostly deciduous and some evergreen trees. Because of this, some shading still occurs in the winter. It was assumed that in the winter seventy percent of the solar radiation reaches the streams. The results of this investigation showed a maximum change in the daily calculation of the net photosynthetic production of DO of  $0.64 \text{ mg L}^{-1}$ . The average change in DO production was  $0.06 \text{ mg L}^{-1}$ . Because the winter months were not considered critical conditions and were not modeled, the affect of the seasonally changing tree canopy was not further considered.

The chlorophyll *a* equation was calculated for all of the sampling stations on the main channel. Table 4 summarizes the input parameters, ranges, and literature references used for calculating the chlorophyll equation. Monthly photoperiods were calculated based on the latitude of the LREW. Table 5 summarizes average monthly solar radiation in Tifton, Georgia. Water temperature readings were collected weekly at gauging station B. Chlorophyll *a* data were collected biweekly at the same site. Figure 13 shows the monthly average of the daily net oxygen production by phytoplankton per month. According to the equation, between  $0.020$  and  $2.6 \text{ mg L}^{-1} \text{ d}^{-1}$  of DO was produced each day throughout the year.

Table 4. Values and ranges used in the chlorophyll equation.

<b>Variable</b>	<b>Value</b>	<b>References and Ranges</b>
<b>I<sub>s</sub></b>	375.00	between 250 and 500; Thomann and Mueller, 1987
<b>I<sub>a</sub></b>	Varies	112 - 289 langleys per day; Thomann and Mueller, 1987
<b>K<sub>e</sub></b>	1.80	Secchi disk depth and Beeton A.M., (1958)
<b>z</b>	0.35	Average depth calculated from cross-sections
<b>a<sub>op</sub></b>	0.15	0.1-0.3; Thomann and Mueller, 1987
<b>G<sub>max</sub></b>	2	1.5 - 3.0 d <sup>-1</sup> ; Thomann and Mueller, 1987
<b>P</b>	Measured	4 – 41 mg L <sup>-1</sup>
<b>T</b>	Measured	4 – 32°C
<b>f</b>	Varies	Monthly calculations based on longitude

Table 5. Average Monthly Solar Radiation for Tifton, Georgia.

<b>Month</b>	<b>Average Solar Radiation (langleys per day)</b>	<b>50% shade (langleys per day)</b>
<b>January</b>	250.63	125.32
<b>February</b>	316.71	158.36
<b>March</b>	403.02	201.51
<b>April</b>	495.67	247.84
<b>May</b>	577.94	288.97
<b>June</b>	532.72	266.36
<b>July</b>	533.41	266.70
<b>August</b>	493.07	246.54
<b>September</b>	393.42	196.71
<b>October</b>	358.61	179.31
<b>November</b>	270.59	135.30
<b>December</b>	224.90	112.45
Solar radiation data from the Georgia Automated Environmental Monitoring Network, University of Georgia, Tifton, Georgia (2004)		

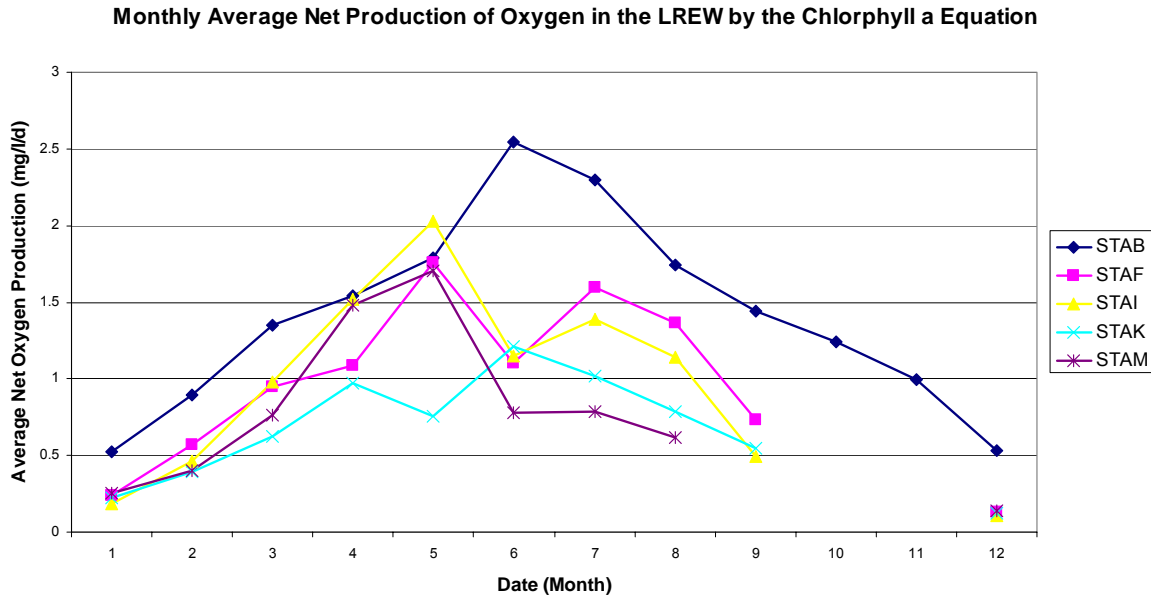


Figure 13. Average net production of photosynthesis in the LREW by the chlorophyll a equation.

Diurnal equation

The third and last method that was considered for calculating the DO production through net photosynthesis was the diurnal equation. Di Toro's (1975) equation (Equation 17) relates the diurnal DO cycle to the production of oxygen in a body of water. In this method, DO is measured periodically throughout one entire day. The rise in DO during daylight and the fall of DO during darkness is used to calculate gross oxygen production. Respiration can then be calculated using the same equations as those used with the chlorophyll a equation. Unlike the light and dark bottle method and the chlorophyll a equation, the diurnal equation does account for oxygen production by rooted aquatic plants and phytoplankton because it measures the fluctuation of oxygen throughout the entire system.

Equation 17. The net photosynthetic production of DO according to Di Torro's diurnal equation.

$$Pa = \left\{ \frac{0.5K_a [1 - \exp(-K_a t)]}{[1 - \exp(-0.5K_a t)]^2} \right\} \Delta C$$

Pa = photosynthetic oxygen production (mg L<sup>-1</sup> d<sup>-1</sup>)

Ka = volumetric reaeration rate coefficient (d<sup>-1</sup>)

t = time (d)

ΔC = the maximum and minimum DO calculation over one day (mg L<sup>-1</sup>)

The daily rise and fall of DO shown in Figure 14 suggests that streams in the LREW may display diurnal DO patterns (Figure 14). Because DoSag is a steady state model, it was not possible to model these diurnal variations in DO. But Di Toro's diel oxygen equation (Equation 17) can still be used to calculate oxygen production from photosynthesis. Table 6 shows the results of the diurnal oxygen production equation.

To conclude this discussion, three methods were considered for calculating the production of oxygen through photosynthesis: light and dark bottles, the chlorophyll a equation, and the diurnal equation. The chlorophyll a equation and the diurnal equation were chosen for further exploration. Diurnal DO data taken from station B during April 2004 indicate that photosynthetic production of oxygen was approximately 1.21 mg L<sup>-1</sup> d<sup>-1</sup> (Table 6). This number is similar to that calculated with the chlorophyll equation for the same month, 1.51 mg L<sup>-1</sup> d<sup>-1</sup>. However, according to the diurnal equation in February of the same year, the oxygen production increased to 4.96 mg L<sup>-1</sup> d<sup>-1</sup>.

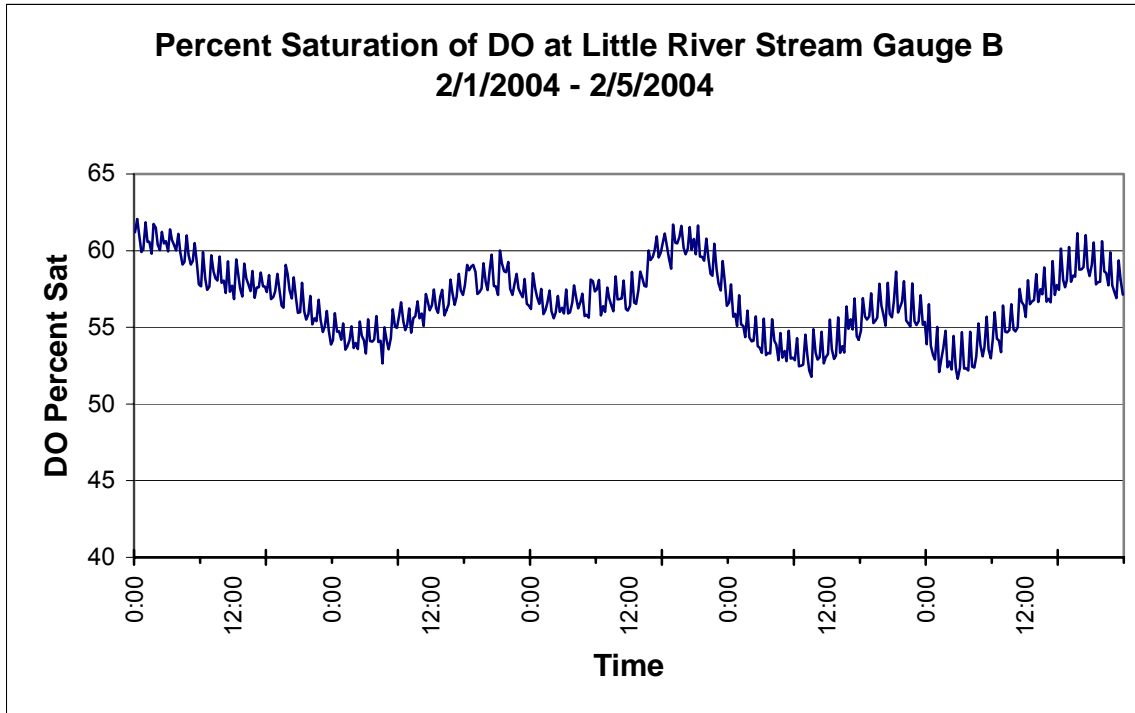


Figure 14. The diurnal pattern of dissolved oxygen at station B. Data from [http://sacs.cpes.peachnet.edu/sewrl/archived\\_data.htm](http://sacs.cpes.peachnet.edu/sewrl/archived_data.htm)

Table 6. Oxygen production computed from the diurnal equation compared to the results of the chlorophyll equation.

Gauging station	Date	Net DO production from the diurnal curve (mg L <sup>-1</sup> d <sup>-1</sup> )	Net DO production from the chlorophyll equation (mg L <sup>-1</sup> d <sup>-1</sup> )
B	February	1.21	0.85
B	April	1.23	1.51
O	February	1.99	Insufficient data
N	February	4.96	Insufficient data

This increase in oxygen production is counterintuitive. Because of the change in temperature and day length, oxygen production should decrease in the winter and increase in the summer. This expected trend is shown with the chlorophyll equation. Because of the incongruity of the diurnal calculations the chlorophyll *a* equation was used to calculate net photosynthetic oxygen production for model input. Monthly averages of daily values were input into DoSag.

### Sediment oxygen demand

SOD is the oxygen used, per unit area and time, during the decomposition of organic material and chemical oxidation in benthic sediments. SOD can represent a large fraction of oxygen consumption in surface waters (Bowie et al., 1985). The understanding of SOD is not complete, as it is a complex system. Influences on SOD include temperature, the oxygen concentration at the interface between the sediment and the water, characteristics of the sediment, the velocity of the water over the sediments, water chemistry, and the biological community (Bowie et al., 1985). Values for SOD range greatly from study to study and from site to site. A literature review of measured values of SOD conducted by Bowie et al. (1985) showed values varying from 0.004 to 14.1 g m<sup>-2</sup> d<sup>-1</sup>. Chapra (1997) stated that average SOD values in enriched streams usually ranged between 1 and 10 g m<sup>-2</sup> d<sup>-1</sup>. Fuss and Smock (1996) found SOD to vary from 0.4 to 12.9 g m<sup>-2</sup> d<sup>-1</sup> in blackwater streams. The same study also found that SOD respiration rates differed between substrata in a blackwater stream. In their study, the highest respiration rate occurred in leaf litter substrata. However, leaf litter exerted a relatively small oxygen demand in this stream overall because areas of leaf litter substrate were not as plentiful as sandy substrate.

Chapra (1997) stated that SOD in streams can be measured two different ways. The first way involves measuring all other known parameters. SOD is then assumed to be whatever oxygen demand is left over. This method assumes that all other parameters were known and measured accurately. This is not a precise method because it may hide sampling errors in other parameters. The second method involves enclosing water and sediments in a chamber. This can be done in-situ or in a laboratory. The oxygen depletion in the chamber is measured over time. The drawback to this method is that the sediments are artificially enclosed in a chamber where they behave differently than they would if they were in a natural stream. In the absence of measured SOD values taken from the LREW and due to the wide range of published values in other areas, SOD estimation for this project involved the former method. All other parameters were measured and a constant value for SOD was chosen based on the remaining DO that needed to be used up.

SOD has been found to increase with increasing temperatures (Zison, et al., 1978). To compensate for this, DoSag internally adjusts for temperature based on the Arrhenious equation and a theta value of 1.065. SOD is input into DoSag as an aerial value. However, in the model SOD is exerted throughout the water depth. To compute this integrated value, the aerial SOD was divided by water depth.

#### Parameter estimation conclusion

Many parameters were considered during this parameter estimation process. Some parameters were measured and some were calculated. Whenever possible, the values were based on the calibration date, March 12, 2004. DO and temp were measured at the sampling locations in the LREW. Skeletonization of the LREW was

done in ArcView using stream network and elevation data. Flow was measured automatically at the eight weirs in the LREW. The production factor was estimated based on contributing watershed area and prorated flow data. The average water depth was based on natural stream cross-sections. The average velocity was based on the flow and depth calculations. Reaeration was calculated according to the Dobbins O'Connor equation. BOD was measured using the long-term BOD test. And finally, SOD was assumed to be the oxygen demand left over, after all of these parameters were estimated. Once all of the parameters were estimated, the calibration process began.

## Chapter4: Calibration

Model calibration is the process of adjusting parameters to make the modeled DO values match the DO values that were measured in the field. Parameters should only be adjusted within appropriate ranges of observed, calculated, or referenced values so that the modeled system maintains a sense of realism. For this project, calibration was the process of tuning the input parameters to make the modeled DO concentrations match measured DO concentrations at each of the sampling locations on a given day.

The purpose of this research was to model DO under marginal or critical conditions. Flows in streams of the coastal plain of Georgia regularly go to zero (Figure 3). Streams under these conditions do not necessary dry up. Instead, water stops flowing and stagnates. When this happens, atmospheric reaeration continues only through diffusion. Under these conditions, the only other parameter adding DO to the stream is photosynthesis. This state of low and no flow is certainly an important factor contributing to low DO in coastal plain Georgia streams. It was not possible to model DO during extreme low flow or no flow conditions because of the nature of the Streeter-Phelps equation (Equation 1). In this equation, velocity is placed in the denominator. So, if velocity approaches or goes to zero then the equation will fail. To avoid this situation, the calibration date was selected for marginal DO and low-flow conditions.

In order to model marginal DO and low flow conditions, the two terms first had to be defined. If daily average DO in a stream falls below  $5.0 \text{ mg L}^{-1}$ , the EPD considers the stream DO impaired (EPD, 1999). Marginal conditions for DO were based on this number and defined as dates when DO approached or fell below  $5.0 \text{ mg L}^{-1}$ . Marginal conditions for flow were defined through an inspection of the relationship between DO and flow. Graphs of flow versus DO were made at each sampling location. For example, Figure 15 shows the relationship between DO and flow at station B. This graph shows that when the flow was greater than  $10000 \text{ L s}^{-1}$ , DO rarely fell below  $5.0 \text{ mg L}^{-1}$ . So, the calibration date was selected from the dates when DO approached  $5.0 \text{ mg L}^{-1}$  and the flow at station B was lower than  $10000 \text{ L s}^{-1}$ . The date that was selected for calibration was March 12, 2004. On this day, dissolved oxygen ranged from  $3.29$  at the headwater to  $6.60 \text{ mg L}^{-1}$  at station B. The flow on March 12, 2004 at station B was  $1400 \text{ L s}^{-1}$ .

Model calibration was conducted by sequentially calibrating various individual parameters. First modeled flow was calibrated so that it matched measured flow. Velocity was calibrated after flow. Then CBOD was calibrated, followed by NBOD. The last parameter that was calibrated was DO. This sequence was based on recommendations made by Dr. Roy Burke (2004). In the final process of calibrating DO, all the parameters that were not previously calibrated were available for tuning including: net photosynthesis, SOD, and reaeration. DoSag does not have an automatic calibration option. Therefore, calibration was conducted using a trial-and-error method.

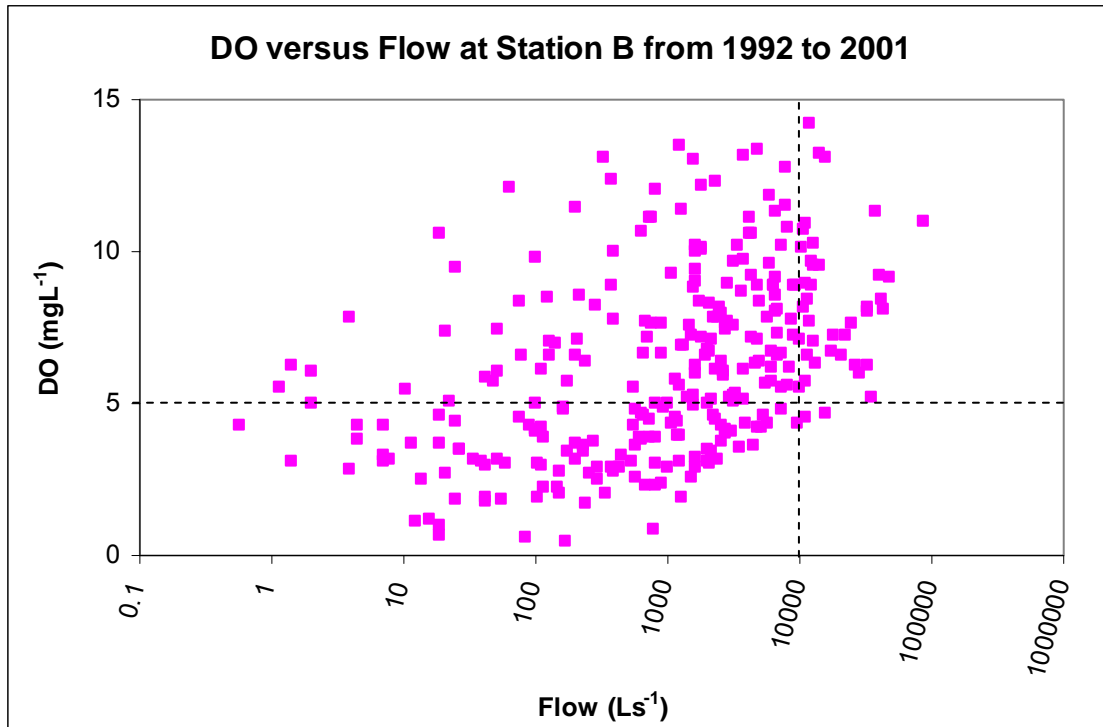


Figure 15. The relationship between DO and flow at station B in the LREW.

### Flow

Flow was input based on a water yield, which is defined as the volume of flow divided by the contributing watershed area. The modeled flow was compared to the measured flow that was collected at each of the gauging stations. Flow needed minimal calibration because of the way it was calculated. The use of the prorated water yield meant that calculated flow closely matched the measured flows.

### Velocity

Velocity values did need to be calibrated. Calculated velocity measurements at station K were unusually high ( $0.54 \text{ m s}^{-1}$ ). In the model, this high velocity increased reaeration and drove DO up. The increase was not reflected in the sampled data. Because of this difference between measured and calculated values, velocity numbers

from station K were discarded and the velocity values for station I were used to represent the reaches that would normally be represented by station K.

#### Carbonaceous biochemical oxygen demand

CBOD was calibrated after flow. Because the modeling was only conducted during flowing conditions, values from the no-flow long-term CBODu test were discarded and only values from the flowing long-term test were considered. The ultimate CBOD that was used was  $6 \text{ mg L}^{-1}$  in the mainstem headwater and  $17 \text{ mg L}^{-1}$  throughout the rest of the watershed. The average CBODu taken during the long-term test was  $13.2 \text{ mg L}^{-1}$ . The calibrated CBODk rate that was used in the model was  $0.04 \text{ d}^{-1}$ . This value was twice the average of the long-term results taken during flowing conditions,  $0.02 \text{ d}^{-1}$ , but similar to the rates from the no-flow conditions. Figure 16 shows that the use of these numbers resulted in CBOD values throughout the mainstem which were close to the sampled long-term CBODu values (Figure 16).

#### Nitrogenous biochemical oxygen demand

NBOD was calibrated after CBOD. The strategy used for NBOD calibration was the same as that used for CBOD. NBODk and NBODu values came from the long-term BOD test conducted during flowing conditions. Calibration involved increasing or decreasing NBODu and NBODk in model reaches to achieve a calibration line that matched the long-term NBODu results. The NBODk rate that was used was  $0.13 \text{ d}^{-1}$ . This was the same as the average NBODk rate that was recorded during the long-term test. The NBODu values used were  $0.5 \text{ mg L}^{-1}$  in the headwater of the mainstem and  $1.7 \text{ mg L}^{-1}$  throughout the rest of the watershed. The average NBOD taken during the

long-term BOD test was  $1.33 \text{ mg L}^{-1}$ . Figure 17 shows that these values resulted in numbers that approximated to the sampled long-term CBOD values.

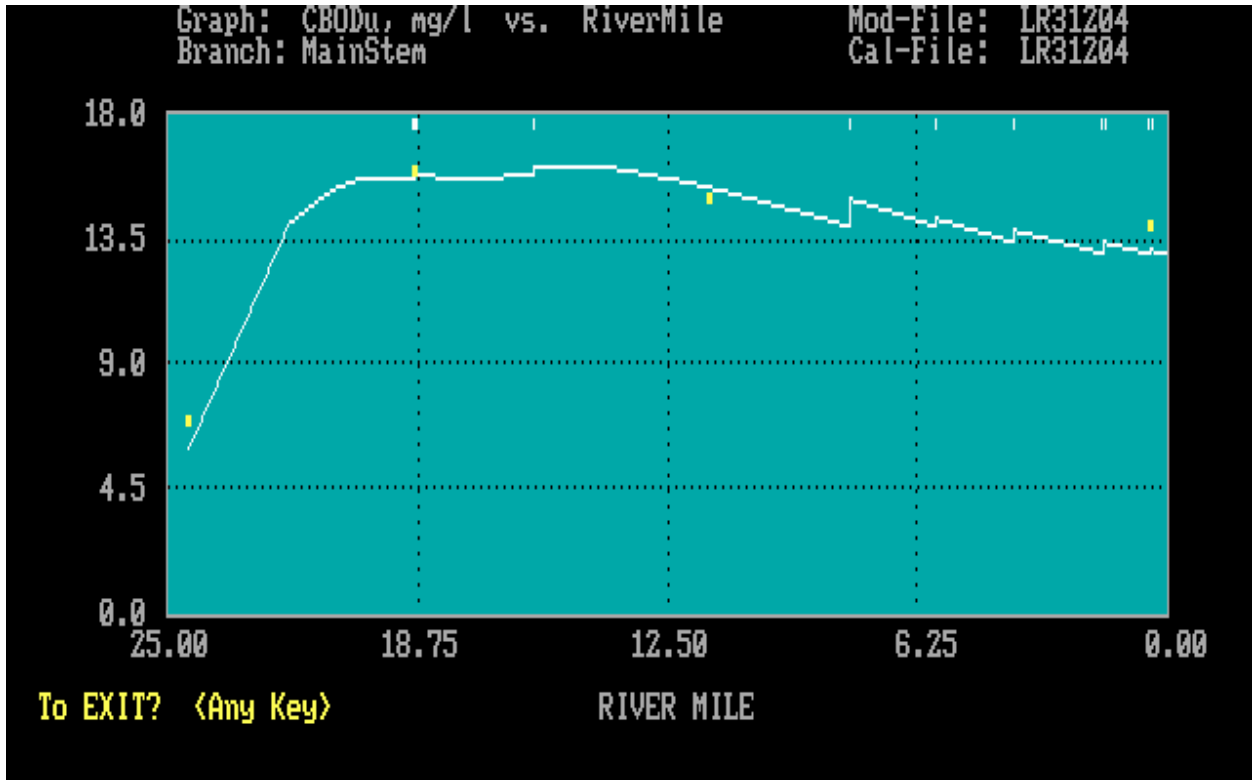


Figure 16. The calibration of CBODu. A CBODu of  $6 \text{ mg L}^{-1}$  was used in the mainstream headwater. A CBODu of  $17 \text{ mg L}^{-1}$  was used throughout the rest of the model. And a CBODk of  $0.04 \text{ d}^{-1}$  was used throughout the model. The yellow rectangles represent measured values and the white line represents the modeled CBODu. The left side of the x axis refers to the headwater of the mainstem. The right side of the x axis refers to the end of the mainstem reach or station B.

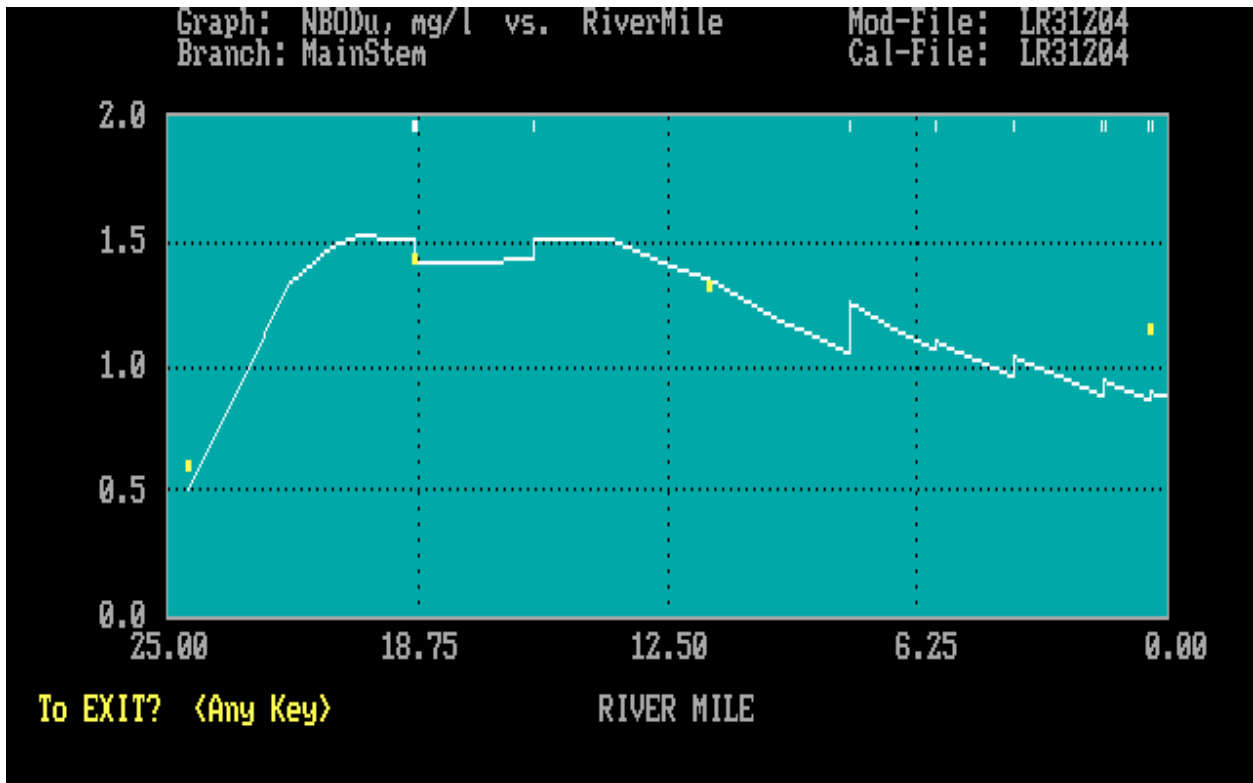


Figure 17. NBODu calibration using a NBODu of 1.7 mg L<sup>-1</sup> and a NBODk of 0.1 d<sup>-1</sup>. The yellow rectangles represent measured values and the white line represents the modeled NBODu. The left side of the graph refers to the headwater of the mainstem. The right side of the graph refers to the end of the mainstem reach.

### Dissolved oxygen

DO was calibrated last. After flow, CBOD, and NBOD were calibrated, the degrees of freedom left for adjustments within the model were watershed configuration, net photosynthesis, SOD, percent saturation, and reaeration. All of these parameters

were considered during the calibration of DO. The following paragraphs describe how each of these parameters was considered.

*Tuning watershed configuration for dissolved oxygen calibration*

During the first calibration run, modeled DO decreased dramatically between stations I and F. This trend was not reflected in the sampled DO data. In the sampled data, on the calibration date, DO decreased only slightly between stations I and F. The surveyed cross-section at station I was channelized (Appendix C). Downstream at station F the cross-section was much more shallow and wide. Up until this point, model parameters were determined by those measured at the nearest downstream gauging station. Parameters for each reach were assumed constant between gauging stations. So the input parameters for reaches 7, 8, 10, 11, and 12 (Figure 7) were all based on the shallow and wide cross-section at station F. A field survey, investigating the configuration of the channel between stations I and F, was conducted to better understand how the channel changed between the two gauging stations.

The investigation of the stream channel revealed that the Little River was quite channelized at each road crossing between I and F. Further downstream, at station F, the stream widened into the swampy configuration. After this investigation, it was decided to use the dimensions and all the other parameters including temperature, NBOD, CBOD, SOD, and percent saturation from station I to represent reaches 7, 8, and 10. The only parameter that was used from station F in these reaches was the water yield. The parameters that were collected at station F were still used just upstream from F in reaches 11 and 12. This change solved the problem of the extreme

drop in DO between stations I and F and the modeled data more closely approximated the sampled data.

#### Tuning net photosynthesis for dissolved oxygen calibration

Up until this point, the production of DO through net photosynthesis was considered to be a constant throughout the stream network. Starting at the headwaters and moving downstream, DO dropped more quickly in the modeled data than it did in the sampled data (Figure 18). An investigation into correcting this drop was conducted.

Three analyses of the relationship between photosynthesis and distance downstream were conducted. As stated previously, the first method was the use of a constant value of  $1.5 \text{ mg L}^{-1} \text{ d}^{-1}$ . This number was based on the chlorophyll a equation for station B during the month of March. Figure 18 shows modeled DO based on the constant value for net photosynthesis.

The second method that was used involved using the chlorophyll a equation to calculate a unique value for net photosynthesis at each of the gauging stations. Net photosynthesis was input into each reach according to the values that were calculated from the chlorophyll a samples collected at the nearest downstream gauging station. Results of this method are shown in Figure 19.

The final method that was used to calculate net photosynthesis involved changing the net production of DO from photosynthesis according to a linear equation. Figure 20 shows that a correlation existed ( $R^2 = 0.83$ ) between river kilometer and the average net photosynthetic production of oxygen, calculated by the chlorophyll a equation. Chlorophyll a concentrations dropped with distance downstream. A linear trend line was fit to the data and a slope of 0.019 was calculated. The average

photosynthetic oxygen production in March at each station was then altered based on equation of the trend line (Figure 20). The model output is displayed in Figure 21.

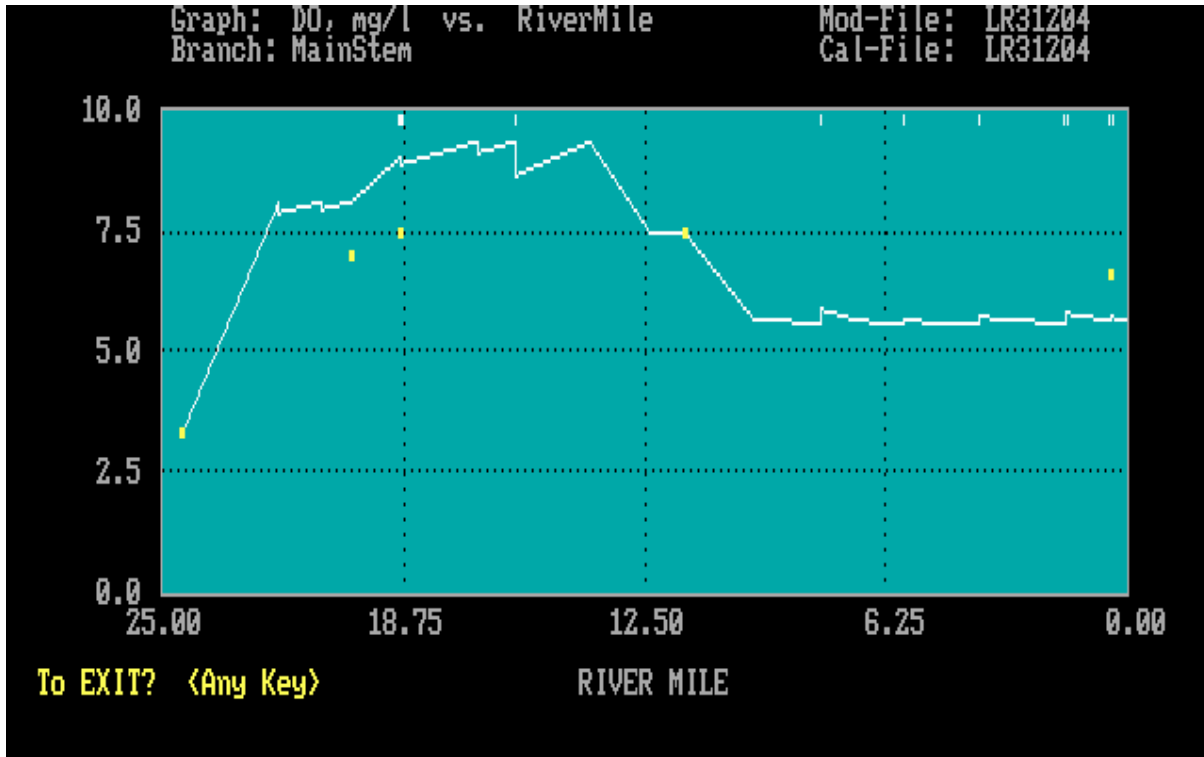


Figure 18. Modeled DO with constant net photosynthesis of  $1.5 \text{ mg L}^{-1} \text{ d}^{-1}$ .

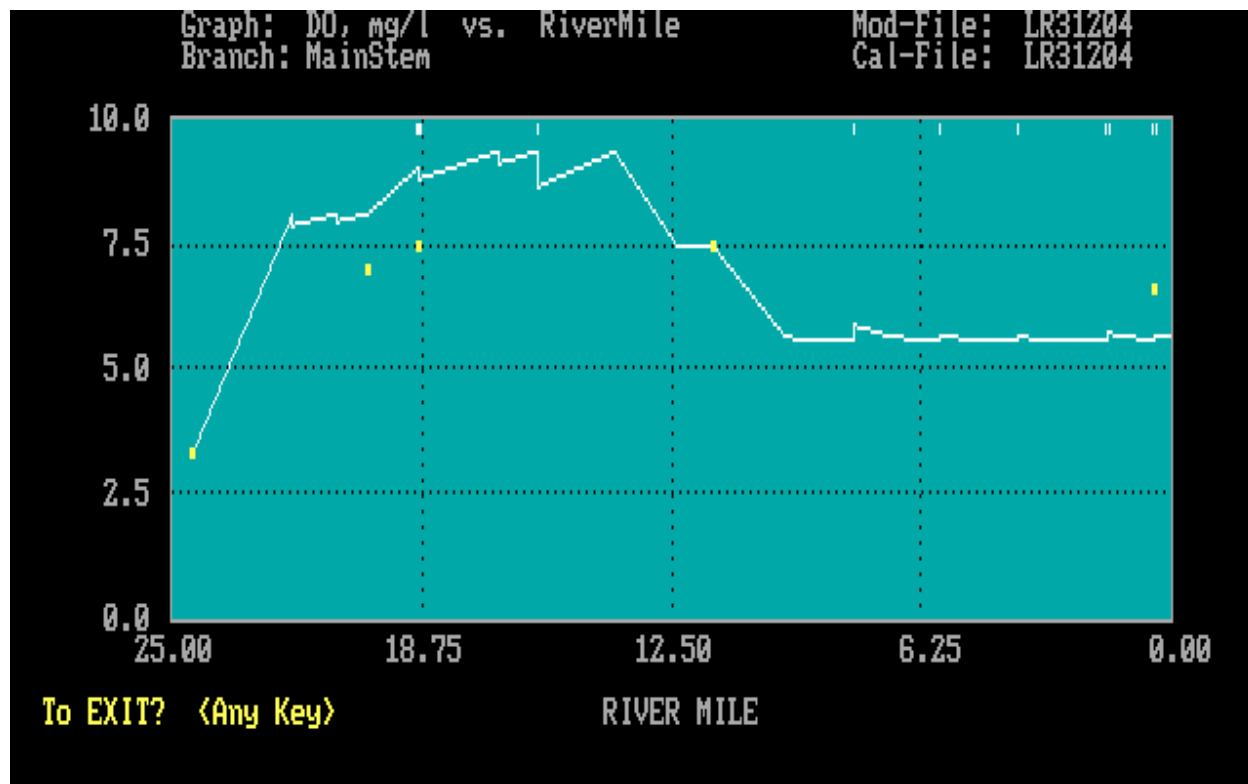


Figure 19. Modeled DO with variable net photosynthesis based on the chlorophyll a equation computed for March at the gauging stations.

Average Annual Net Photosynthetic Production of Oxygen by the Chlorophyll a Equation Versus River Kilometer

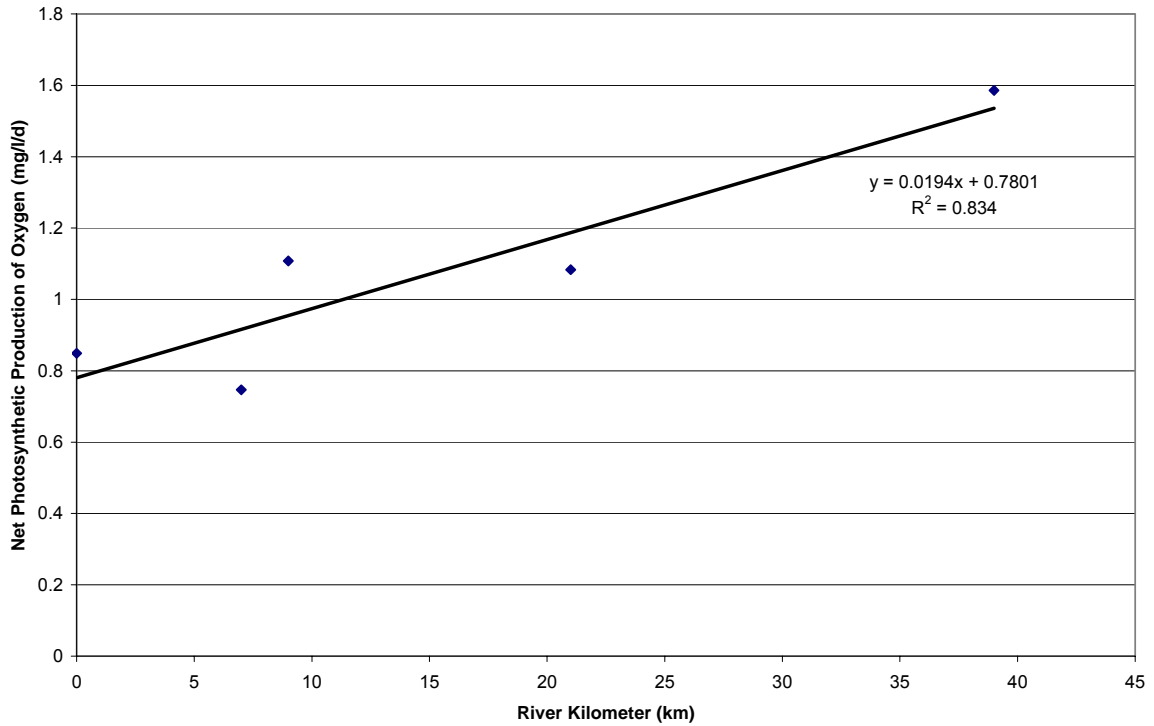


Figure 20. The relationship between the net photosynthetic production of oxygen by the chlorophyll equation and river kilometer. The diamonds represent the net photosynthetic production of oxygen calculated at each gauging station.

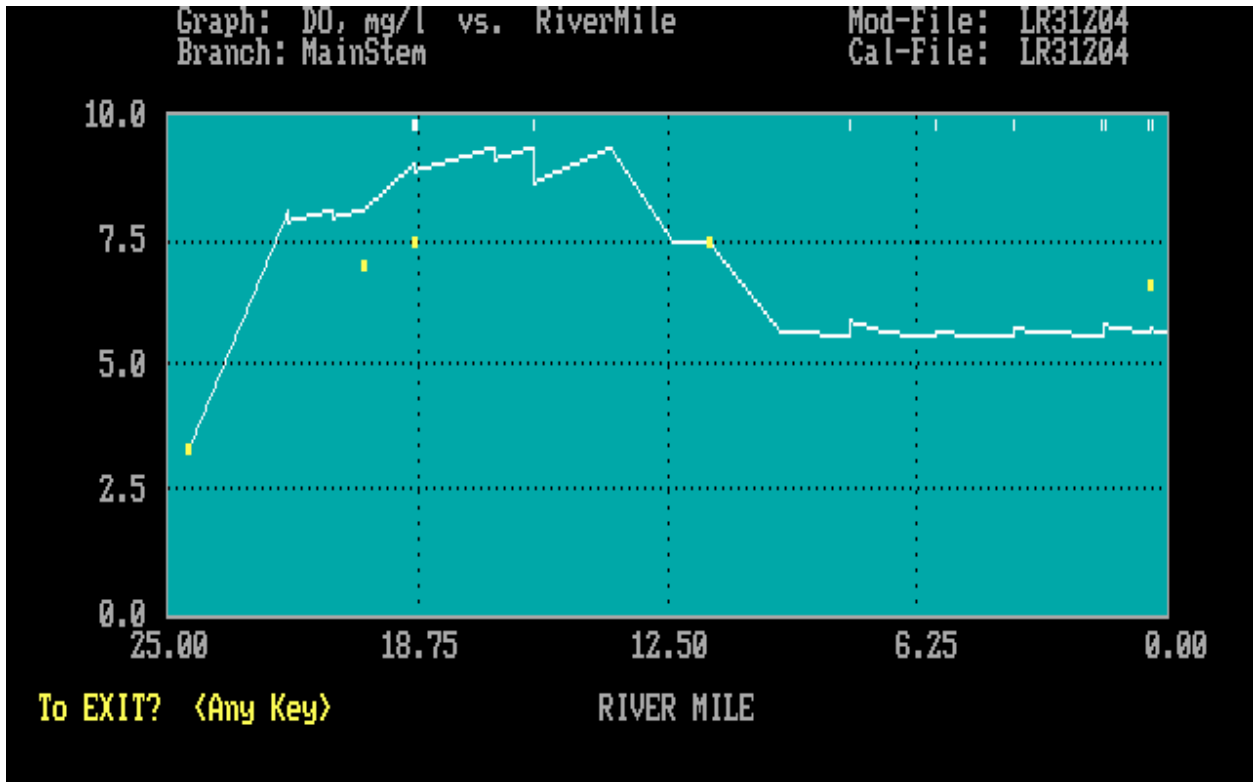


Figure 21. Modeled DO with variable net photosynthesis based on the trend line in Figure 20.

The three methods that were used for computing the net photosynthetic production of oxygen resulted in almost identical model outputs. Surprisingly, the use of a constant input of  $1.5 \text{ mg L}^{-1} \text{ d}^{-1}$  resulted in, if not the best fit, then as good a fit as the other options. Therefore, the net photosynthetic production of oxygen was input as a constant. The number that was used was calculated using the chlorophyll a equation and represented the average monthly net production of DO at station B.

Tuning sediment oxygen demand for dissolved oxygen calibration

SOD was also initially represented as a constant value. The value of  $6 \text{ g m}^{-2} \text{ d}^{-1}$  fell in the middle of the range of published values (see the Parameter Estimation

chapter). Figure 22 shows that the LREW's slope is generally steeper in the upper reaches and the gradient is shallower toward the end of the watershed. It was qualitatively observed that sediments in the upper reaches were sandier and cleaner than those in the lower reaches. In the lower swampy reaches, sediments appeared muddier containing sticks and decomposing leaves. Because of these observations, the relationship between SOD and channel slope was considered. Decreasing SOD in the reaches with steeper slopes and increasing it in the reaches with shallower slopes would result in an overall increase in DO in the downstream direction. But, in the calibration scenario, DO needed to be lower in the upper reaches and higher in the lower reaches. So, increasing SOD in the downstream reaches would have the opposite of the desired effect.

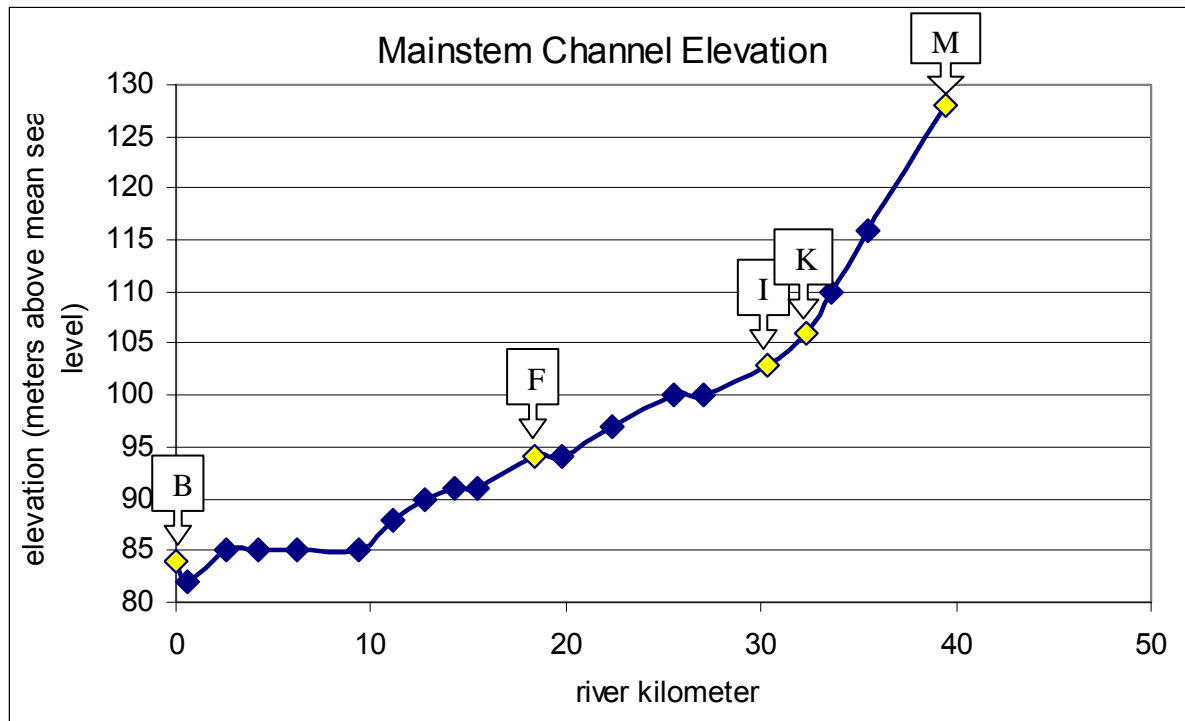


Figure 22. Elevation versus river kilometer in the LREW.

### Tuning reaeration for dissolved oxygen calibration

The O'Connor Dobbins equation for reaeration was chosen over the Tsivoglou equation, for reasons stated in the Parameter Estimation chapter. However, an investigation using both equations as well as using direct input was conducted to understand how the equations for calculating reaeration specifically affected model output. When modeling with the O'Connor Dobbins equation, a SOD value of  $6 \text{ g m}^{-2} \text{ d}^{-1}$  resulted in reasonable DO concentrations (Figure 18). However, when using the Tsivoglou equation, SOD had to be reduced to a value of  $3 \text{ g m}^{-2} \text{ d}^{-1}$  to achieve reasonable DO concentrations (Figure 23). The use of the Tsivoglou equation also resulted in a much more jagged representation of DO. This was due to there being zero reaeration in reaches with zero slopes; DO quickly dropped to hypoxic or anoxic conditions in these reaches. Lowering the SOD to  $3 \text{ g m}^{-2} \text{ d}^{-1}$  helped to bring the DO back up, but did not resolve the steep drops in DO concentrations due to zero slopes.

The use of a constant value for the reaeration rate was also investigated. Figure 24 shows that a rate of  $3 \text{ d}^{-1}$  resulted in reasonable DO concentrations when using direct input. The constant reaeration rate did not represent the DO drop in the downstream reaches. After comparing the results from the three methods of calculating reaeration, the O'Connor Dobbins equation was again chosen for use in the calibrated model.

### Tuning percent saturation for dissolved oxygen calibration

It was assumed that the relationship between the DO in undelinated tributaries and the measured DO at the nearest downstream gauging location was constant

throughout the watershed. Calibrating percent saturation of lateral flow was considered. However, there was no physical reason for increasing DO in tributaries or groundwater in the downstream direction. So, the DO concentration in lateral flow was assumed to be the same as that measured at the nearest downstream gauging station.

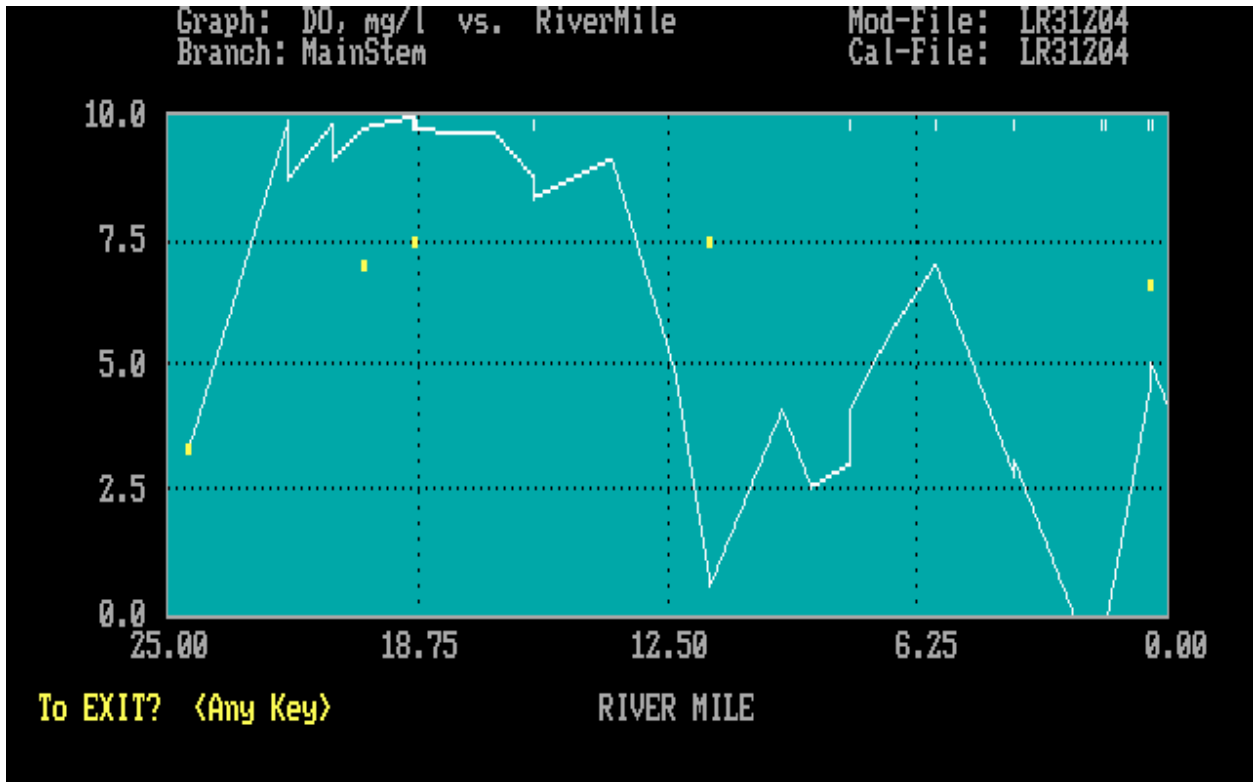


Figure 23. Reaeration by the Tsivoglou equation.  $SOD = 3 \text{ g m}^{-2} \text{ d}^{-1}$ .

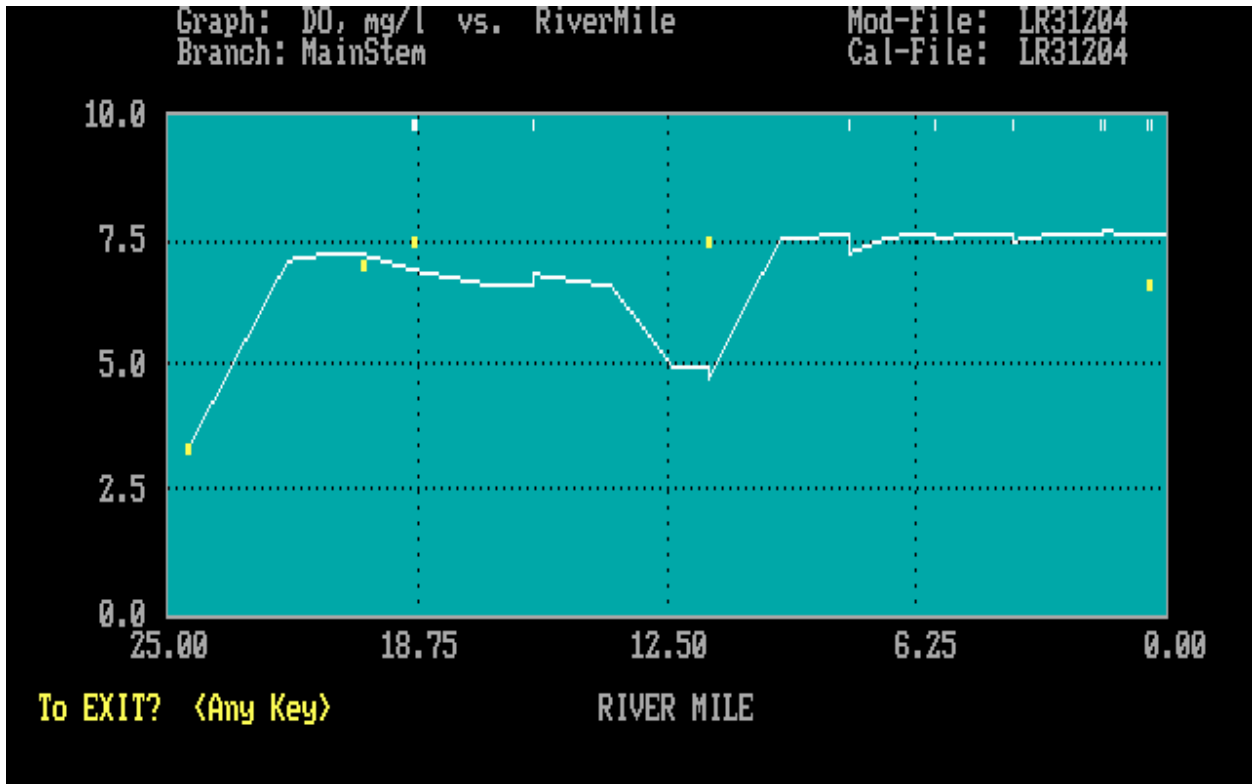


Figure 24. Modeled DO using a direct input of  $3 \text{ d}^{-1}$  for the reaeration rate.

Summary of calibrated parameters

Table 7 summarizes the parameters that were used as inputs for the final calibration. NBODu, CBODu, NBODk, velocity, SOD, and watershed configuration were adjusted. All of the other parameters were input as they were calculated in the Parameter Estimation chapter.

Table 7. Calibrated parameters throughout the LREW on March 12, 2004.

<b>Parameter</b>	<b>Calibration Value</b>
<b>CBOD<sub>u</sub></b>	*17 mg L <sup>-1</sup>
<b>NBOD<sub>u</sub></b>	**1.7 mg L <sup>-1</sup>
<b>CBOD<sub>k</sub></b>	0.04 d <sup>-1</sup>
<b>NBOD<sub>k</sub></b>	0.13 d <sup>-1</sup>
<b>SOD</b>	6 g m <sup>-2</sup> d <sup>-1</sup>
<b>Water temperature</b>	11.64 - 12.86°C
<b>Net photosynthesis</b>	1.5 mg L <sup>-1</sup> d <sup>-1</sup>
<b>Reaeration</b>	O'Connor Dobbins formula
<b>Depth</b>	0.23 – 0.57 m
<b>Velocity</b>	0.018 - 0.16 m s <sup>-1</sup>
<b>Water yield</b>	-5 to 11 L s <sup>-1</sup> km <sup>-2</sup>
<b>DO</b>	3.29 – 9.13 mg L <sup>-1</sup>

\* 6.0 mg L<sup>-1</sup> in the headwater

\*\* 0.5 mg L<sup>-1</sup> in the headwater

## Chapter 5: Sensitivity Analysis

Sensitivity analysis is the process of varying parameters within published or reasonable ranges and observing how those changes affect the model output. A sensitivity analysis is conducted on the calibrated model. For the purposes of this research, there were several objectives for sensitivity analysis. First, the process was useful for revealing which parameters were the most sensitive to change. Sensitivity analysis was also used to guide data collection and to understand how parameter uncertainty affected model output. Because there were multiple purposes for sensitivity analysis, multiple strategies were employed to understand how parameters affected model output.

A true comparison of the sensitivity of the input parameters can not be made. The process is like “comparing apples to oranges.” First, the parameters are not the same dimensionally. For example, some parameters represented rates and some represented loads. Second, the ranges for each parameter came from different studies that were conducted in different locations. And finally, some parameter ranges are broader than others. These issues present serious dilemmas to interpreting a sensitivity analysis. Yet, the process was still useful for gaining a qualitative description of the system.

### Guiding data collection

The first sensitivity analysis was conducted to guide data collection. After initial work on parameter estimation was done, the system was modeled. Parameters were then increased or decreased by fifty percent and the model output was reanalyzed. During the rest of the parameter estimation process, heavier emphasis was placed on finding appropriate numbers for the most sensitive parameters. This exercise revealed that SOD and reaeration were the two most sensitive parameters. Unfortunately, these parameters were not measured during this project. Following in importance were velocity, depth, and net photosynthesis. The sampling schedule was revised based on the need for appropriate representations of these parameters.

### Uncertainty of parameters

DoSag does not have an uncertainty analysis option. So, total model uncertainty was not considered. However, it was possible to understand what the uncertainty of individual parameters had on the outcome of the model. Modeled parameters were manipulated within the range of their measured values. If a parameter was not measured then it was manipulated within the range of values cited in the literature. Results from this sensitivity analysis to are shown in Table 8. The number represented in the table under the heading "Change in DO" came from the end of the model at station B. This location usually represents the greatest change because it experiences the most cumulative effect. The exercise showed the relative importance of using accurate numbers.

An example of the uncertainty analysis that is shown in Table 8 will be explained for illustrative purposes. Fuss and Smock found SOD to vary between 0.4 - 12.9 g m<sup>-2</sup>

$d^{-1}$  in blackwater streams. The calibrated value of SOD was  $6 \text{ g m}^{-2} \text{ d}^{-1}$ . The modeled DO concentration at station B, using the calibrated value for SOD, was noted. The model was then run with an SOD of 0.46 and  $12.9 \text{ g m}^{-2} \text{ d}^{-1}$ , the upper and lower ranges noted by Fuss and Smock. In this case, increasing parameter was interpreted to mean increasing SOD which in turn decreased DO. The change in DO was noted and is recorded in the table under "Change in DO."

Again, reaeration was shown to be the most sensitive parameter and SOD was the second most sensitive parameter. Surprisingly, a change in water temperature of only one degree resulted in a  $0.49 \text{ mg L}^{-1}$  change in DO. This resulted in a greater change in DO than when CBOD<sub>u</sub> was tripled. Note also that changing the reaeration equation to the Tsivoglou equation resulted in a  $17 \text{ mg L}^{-1}$  drop in DO; the DO dropped from  $5.6$  to  $-11.4 \text{ mg L}^{-1}$ . DoSag allows levels of DO to drop below zero. This is a serious limitation inherent in the model and the implications will be discussed in the Summary and Conclusions chapter.

#### *How sensitive the model was to changes in parameters*

The last type of sensitivity analysis that was conducted was designed to understand how sensitive the model was to changes in parameters. The range of numbers came from increasing or decreasing parameters by fifty percent of the calibrated model. This sensitivity analysis is similar to the data collection sensitivity analysis, but was done on the final calibrated model. Results are shown in Table 9. Water temperature had to be treated slightly differently. If the temperature was increased by fifty percent and measured DO stayed the same then the water would be

Table 8. Results of the sensitivity analysis for uncertainty of parameter estimation.

Parameter	Change in DO (mg L <sup>-1</sup> )		Range used for sensitivity analysis	Reference for range
	Increase parameter	Decrease parameter		
<b>Reaeration formula</b>	Not applicable	-17	Tsivoglou vs O'Connor Dobbins	Options supplied in the DoSag model
<b>SOD</b>	-5.57	6.49	0.4-12.9 g m <sup>-2</sup> d <sup>-1</sup>	Range for blackwater streams (Fuss and Smock, 1996)
<b>Net photosynthesis</b>	0.78	-0.97	0.3-3 mg L <sup>-1</sup> d <sup>-1</sup>	Range for moderately productive streams (Thomann and Mueller, 1987)
<b>Water temperature</b>	-0.49	0.49	+/-1°C	Range between upstream and downstream readings
<b>CBODk</b>	-0.18	0.09	0.01 – 0.05 d <sup>-1</sup>	range of sampled data from long-term BODs
<b>CBODu</b>	-0.14	0.07	7.1 - 23 mg L <sup>-1</sup>	range of sampled data from long-term BODs
<b>NBODu</b>	-0.03	0.06	0.6 – 4.2 mg L <sup>-1</sup>	range of sampled data from long-term BODs
<b>NBODk</b>	-0.02	0.01	0.08 – 0.26 d <sup>-1</sup>	range of sampled data from long-term BODs

supersaturated. To solve this problem, water temperature was altered by only five degrees. The results were similar to the two previous sensitivity analyses. Reaeration and SOD were found to be the two most sensitive parameters.

Table 9. Results of the sensitivity analysis for understanding dominant mechanisms.

Parameter	Change in DO (mg L <sup>-1</sup> )		Range used for sensitivity analysis
	Increase parameter	Decrease parameter	
<b>Reaeration rate</b>	1.07	7.30	+/-50%
<b>SOD</b>	-2.82	2.82	+/-50%
<b>Velocity</b>	0.94	-2.09	+/-50%
<b>Water Temperature</b>	-2.95	1.95	+/-5°C
<b>Depth</b>	0.66	-1.26	+/-50%
<b>DO saturation of lateral flow</b>	0.45	-0.03	+/-50%
<b>CBOD<sub>u</sub></b>	-0.13	0.13	+/-50%
<b>CBOD<sub>k</sub></b>	-0.11	0.09	+/-50%
<b>NBOD<sub>u</sub></b>	-0.40	0.02	+/-50%
<b>NBOD<sub>k</sub></b>	-0.02	0.09	+/-50%

The parameters were also increased and decreased by 0, 25, 50, 75, and 100 percent. The results were charted to understand how the magnitude of changing parameters affected DO (Figure 25). For the purpose of visual clarity, only the most

sensitive parameters were included in the graph. Note the lopsided nature of parameters like reaeration and velocity. When these parameters approached zero, DO at station B quickly dropped to negative values.

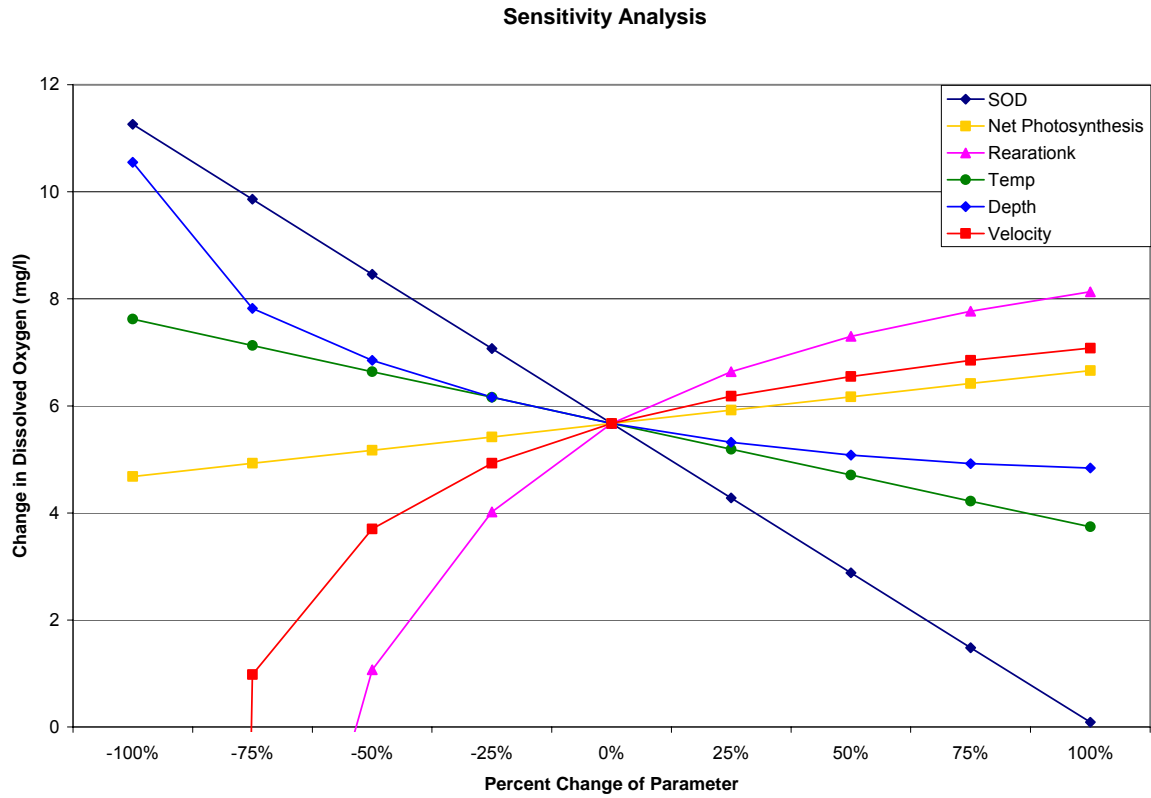


Figure 25. Results of the sensitivity analysis. Only the most sensitive parameters are shown.

## Chapter 6: Validation

Validation is the process of running a calibrated model under different conditions than those used for calibration in order to see if the model can still represent the system. The calibrated parameters are not adjusted during validation. For this research, calibration involved modeling DO on various dates and in another watershed to understand how well the calibrated model represented measured DO values in a range of scenarios.

Theoretically, it is impossible to validate a model and only possible to invalidate a model. This is because all circumstances and scenarios cannot be modeled. Nor is it possible to have observed data for all circumstances and scenarios. Given this, validation is still useful for understanding if a model is capable of representing a system under various conditions.

Zero flow is a significant factor to consider when modeling critical conditions for low DO. However, according to Equation 1, DoSag will fail as velocity approaches zero. So, the model was not run on days with zero flow. The model was run on a range of marginal flow conditions to gain insight into what the model could represent before failing.

To aid the process of data organization, a database was created in Microsoft Access that linked DO, flow, temperature, and various other water quality parameters together on the appropriate dates. The validation dates were selected based on visual

inspection of the data. The first criterion for selecting a validation date was that all necessary data were available for the day. After making sure that the necessary data were available, several strategies were employed for choosing a validation date. The following is a list of questions that address those strategies:

- Is the model capable of representing low flow situations?
- What low velocity conditions make the model fail? Is the model capable of representing high flow situations?
- Can the model simulate low, medium and high DO scenarios?
- Can the model represent the system under various temperatures?
- Can the calibrated model be used on another watershed?

A description of the calibration scenario and each of the eight validation scenarios is listed below.

3/12/2004 – The calibration in the LREW (Figure 26). Flow at station B was 1400 L s<sup>-1</sup>. Water temperature ranged between 11.6 and 16.0°C. The measured DO at station B was 6.6 mg L<sup>-1</sup>. Modeled DO ranged from 3.29 to 9.13 mg L<sup>-1</sup>.

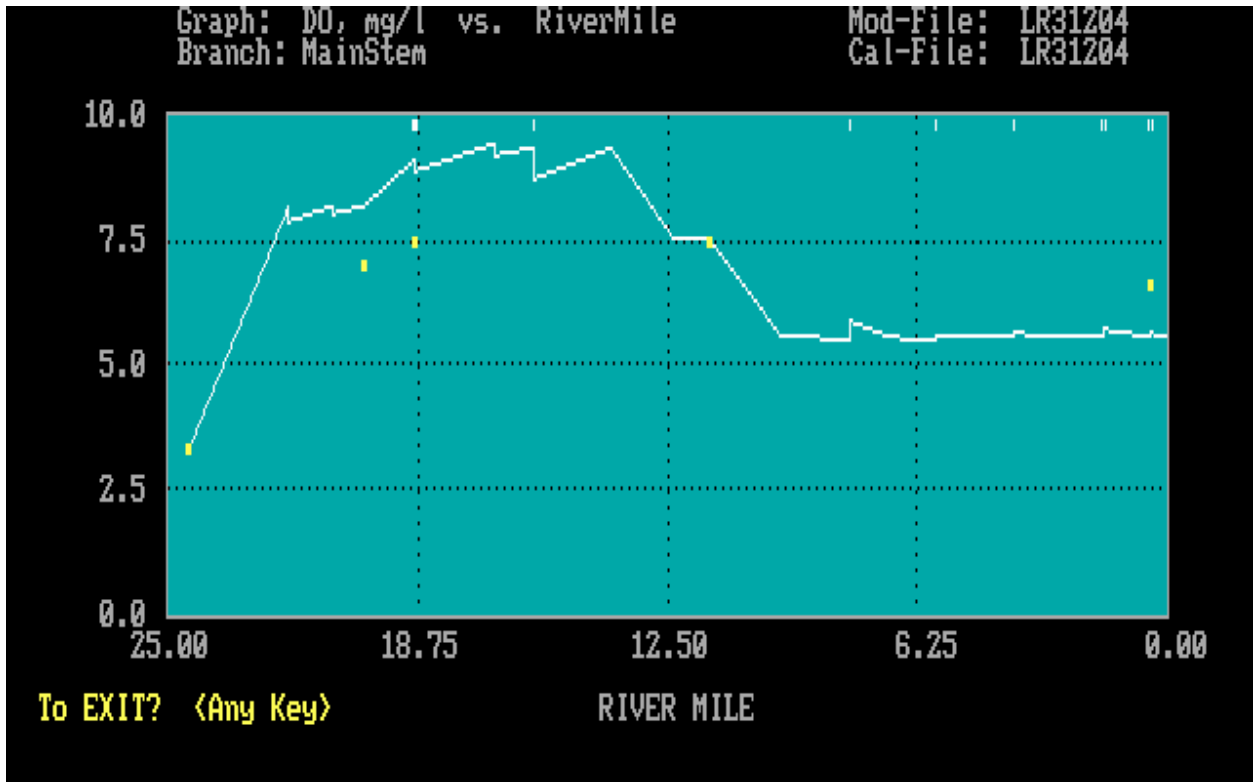


Figure 26. DoSag results from the calibrated model.

Validations in time

5/9/1996 – (Figure 27) Validation in the LREW on a date when the flow at station B was similar to the flow on the calibration date. However, the DO was much lower and the water temperature was much higher. The flow at station B was  $1250 \text{ L s}^{-1}$  as opposed to  $1400 \text{ L s}^{-1}$  on the calibration date. The DO at station B was lower than on the calibration date:  $3.1 \text{ mg L}^{-1}$  versus  $6.6 \text{ mg L}^{-1}$ . On the calibration day, temperatures ranged between  $11.6$  and  $16.0^\circ\text{C}$ . Temperatures on this validation date were much warmer ranging between  $21.7$  and  $27.2^\circ\text{C}$ . The net oxygen production through photosynthesis was recalculated based on the monthly average chlorophyll a data. Velocity and depth were recalculated based on the continuity equation, gauge data, and

cross sectional area. The percent saturation of DO from lateral flow was changed to reflect the measured values on the validation date. All other variables including NBODu, NBODk, CBODu, CBODk, skeletonization, slope, channel length, and watershed area remained constant. These variables remained constant in all scenarios throughout the validation process. This validation shows how the model did not represent the system well at high water temperatures. The DO in the system dropped to negative values in the downstream swampy reaches.

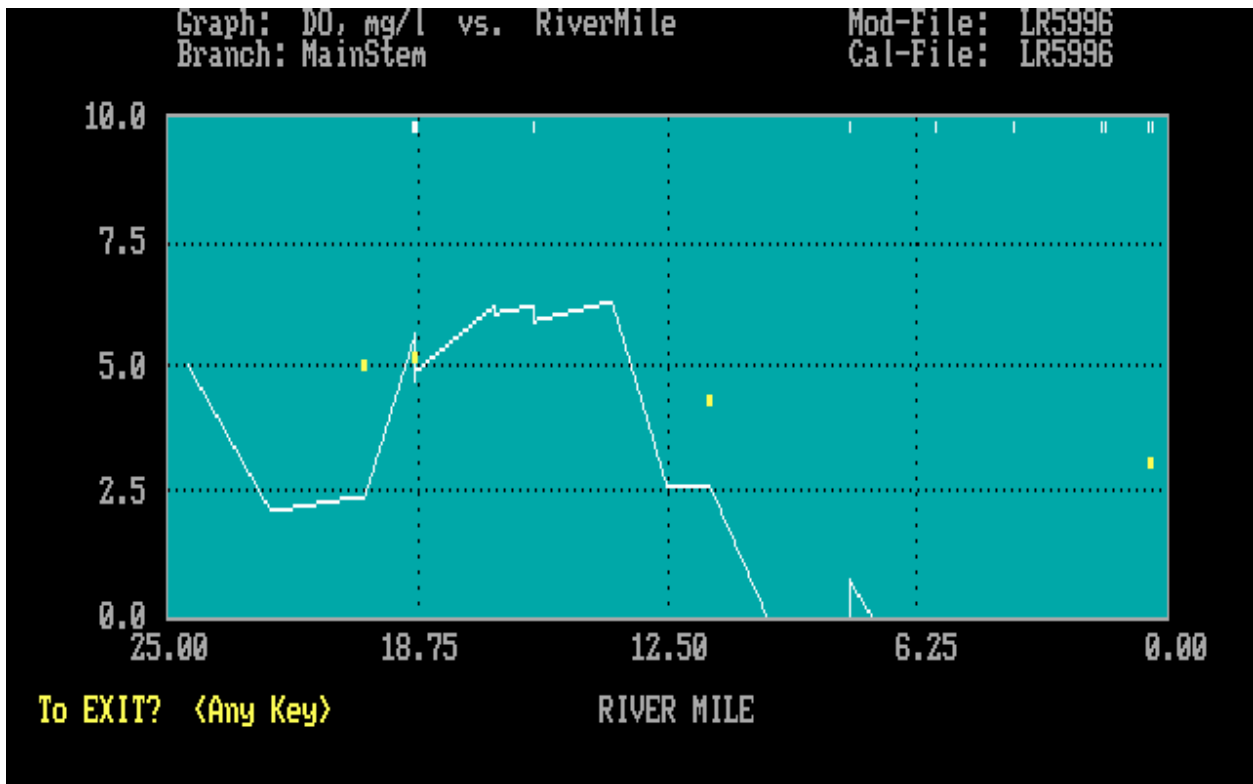


Figure 27. DoSag results from the validation on 5/9/1996.

4/24/1996 – (Figure 28) Validation in the LREW on a date when the flow at station B was about the same as it was on the calibration date. Temperatures were warm, ranging from 17.25 to 19.22°C, but not as hot as on the previous validation for May 9, 1996. The measured DO was lower at station B than on the calibration date. As with all temporal validations, the water yields, average velocities, average depths, percent DO saturation from lateral flow, and net photosynthesis were recalculated for this validation run. Figure 28 shows that the model was able to represent low DO under mildly warm temperatures.

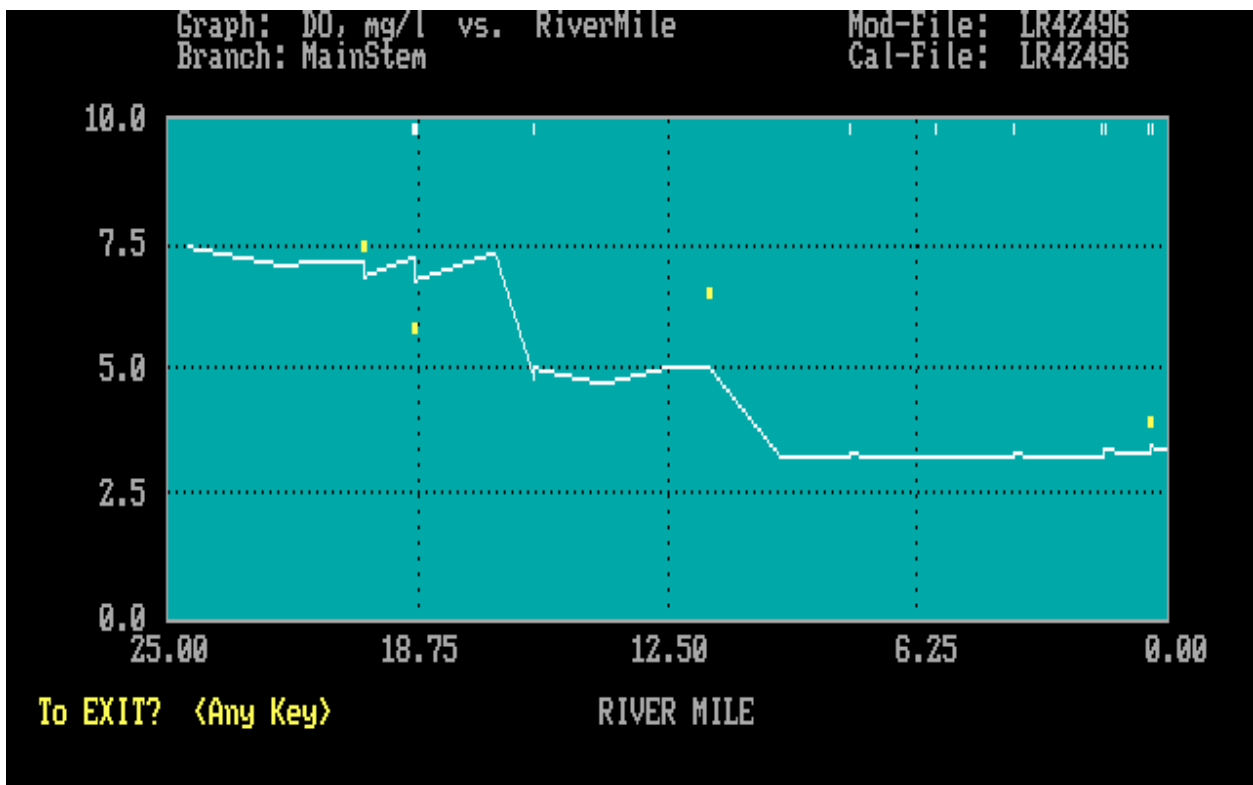


Figure 28. DoSag results from the validation on 4/24/1996.

4/18/1996 – (Figure 29) Validation in the LREW one week before the previous validation on 4/24/1996. Flow was about twice as much at station B as it was on the calibration date and on 4/24/1996. So, apparently it rained before this validation date and the model still did a good job representing the system. The water yields, average velocities, average depths, percent DO saturation from lateral flow, and net photosynthesis were recalculated for this validation run.

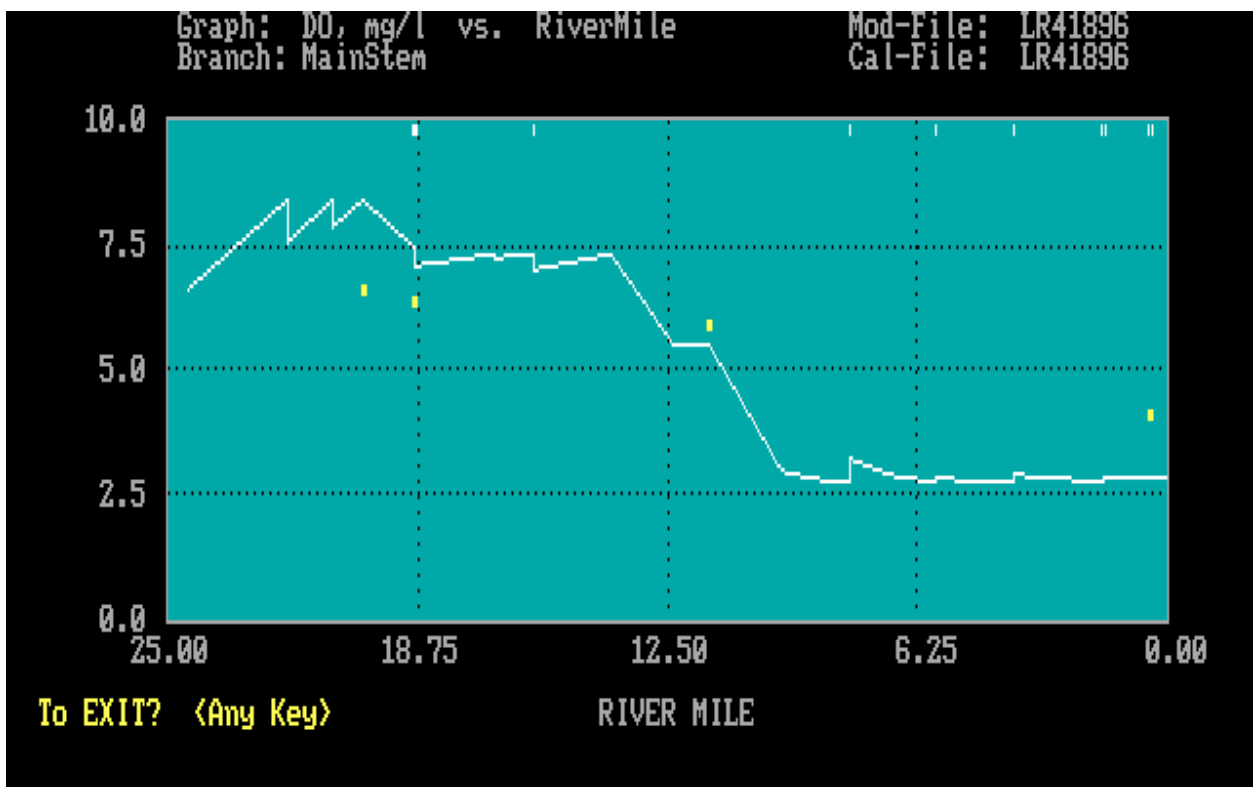


Figure 29. DoSag results from the validation on 4/18/1996.

4/22/1993 – (Figure 30) Validation in the LREW on a date when the flow at station B was 1010 L s<sup>-1</sup>. This is slightly less than the flow on the calibration date. Temperatures on the validation date were somewhat warmer ranging from 13.6 to 16.3°C. The measured DO on this date ranged from 5.02 to 9.0 mg L<sup>-1</sup> which is higher than the DO range on the calibration date. The water yields, average velocities, average depths, percent DO saturation from lateral flow, and net photosynthesis were recalculated for this validation run. Figure 30 shows that the model was also able to represent high levels of DO under marginal flow conditions fairly well.

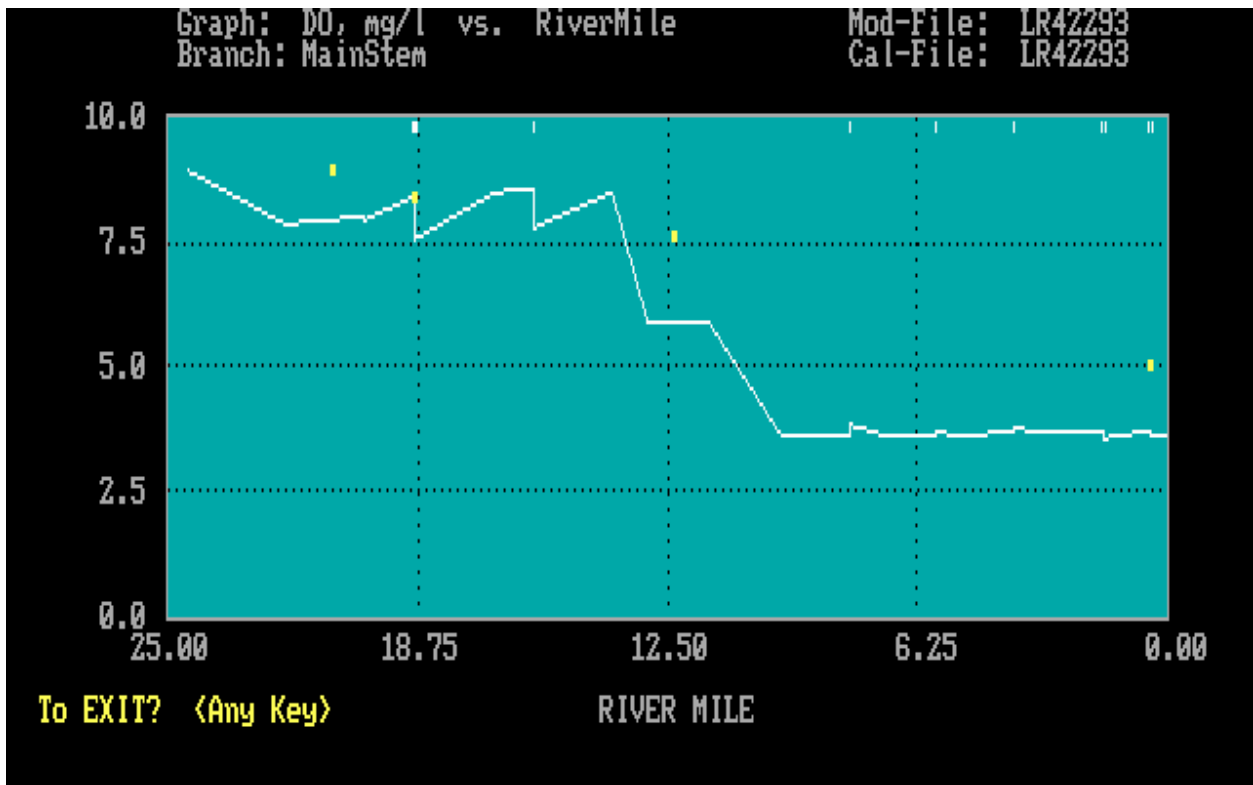


Figure 30. DoSag results from the validation on 4/22/1993.

9/2/1994– (Figure 31) Validation in the LREW on a date when the flow was lower at station B than on the calibration date. The flow on this day was  $570 \text{ L s}^{-1}$ , compared to  $1400 \text{ L s}^{-1}$  on the calibration date. Temperature was very warm ranging from  $23.7$  to  $27.5^\circ\text{C}$ . The measured DO ranged from  $2.56$  to  $6.16 \text{ mg L}^{-1}$ . The system was represented accurately in the channelized upper reaches. However, DO fell to negative values in the wider swampy reaches. Again, the water yields, average velocities, average depths, percent DO saturation from lateral flow, and net photosynthesis were recalculated for this validation run.

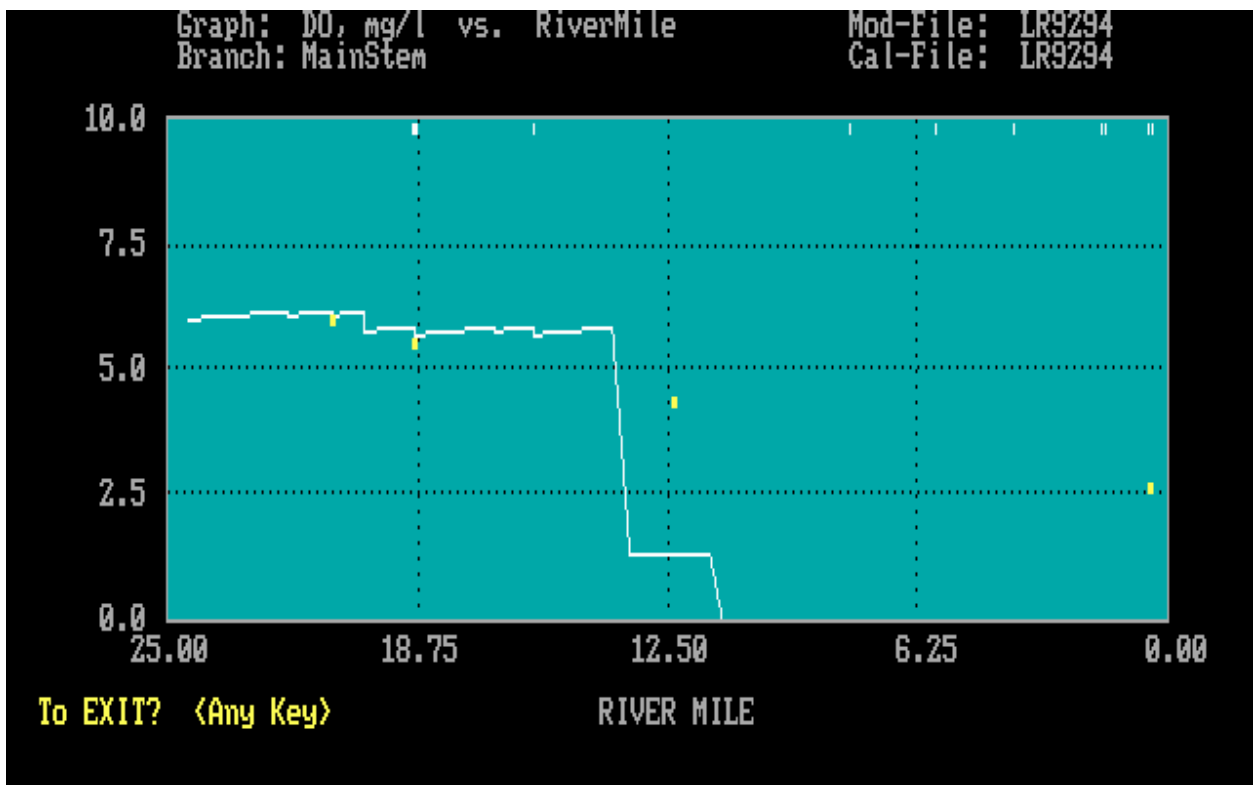


Figure 31. DoSag results from the validation on 9/2/1994.

5/12/1997 – (Figure 32) Validation in the LREW on a date with the lowest flow scenario that was modeled for this research. Flow at station B was  $150 \text{ L s}^{-1}$ . Flow at station K was very low at  $2.3 \text{ L s}^{-1}$ . Water temp was not unusually high and ranged from  $17.2$  to  $18.5^\circ\text{C}$ . DO was rather low ranging from  $2.76$  to  $6.43 \text{ mg L}^{-1}$ . The lowest DO occurred at station B where it dropped to  $2.76 \text{ mg L}^{-1}$ . And again the water yields, average velocities, average depths, percent DO saturation from lateral flow, and net photosynthesis were recalculated for this validation run. Note that even with this very low flow, DO did not drop to negative values.

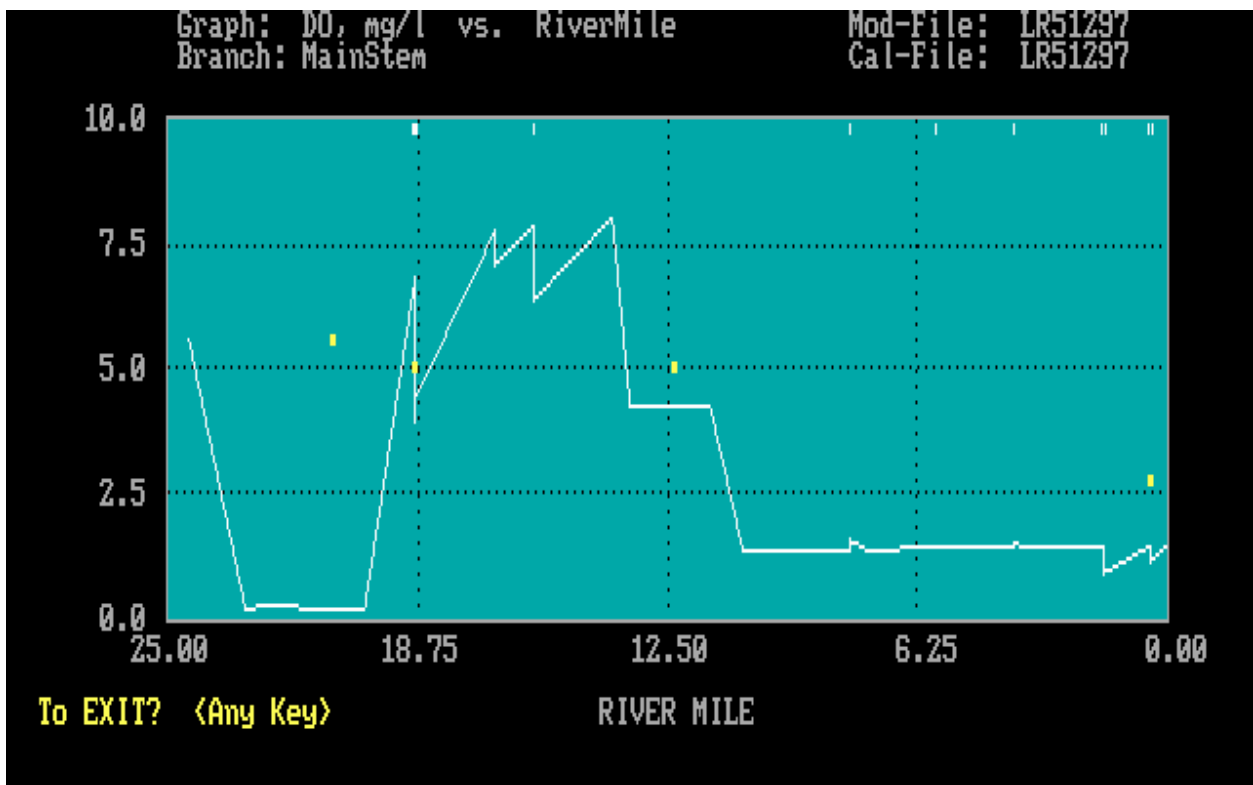


Figure 32. DoSag results from the validation on 5/12/1997.

10/18/1996– (Figure 33) Validation in the LREW on a date when the flow was lower than it was on the calibration date. Flow at station B was  $890 \text{ L s}^{-1}$ . The water temperature was fairly high and ranged from  $18.6$  to  $20.7^\circ\text{C}$ . DO was at the critical stage and ranged from  $2.34$  to  $5.56 \text{ mg L}^{-1}$ . DO was especially low at station B dropping to  $2.34 \text{ mg L}^{-1}$ . The water yields, average velocities, average depths, percent DO saturation from lateral flow, and net photosynthesis were recalculated for this validation run.

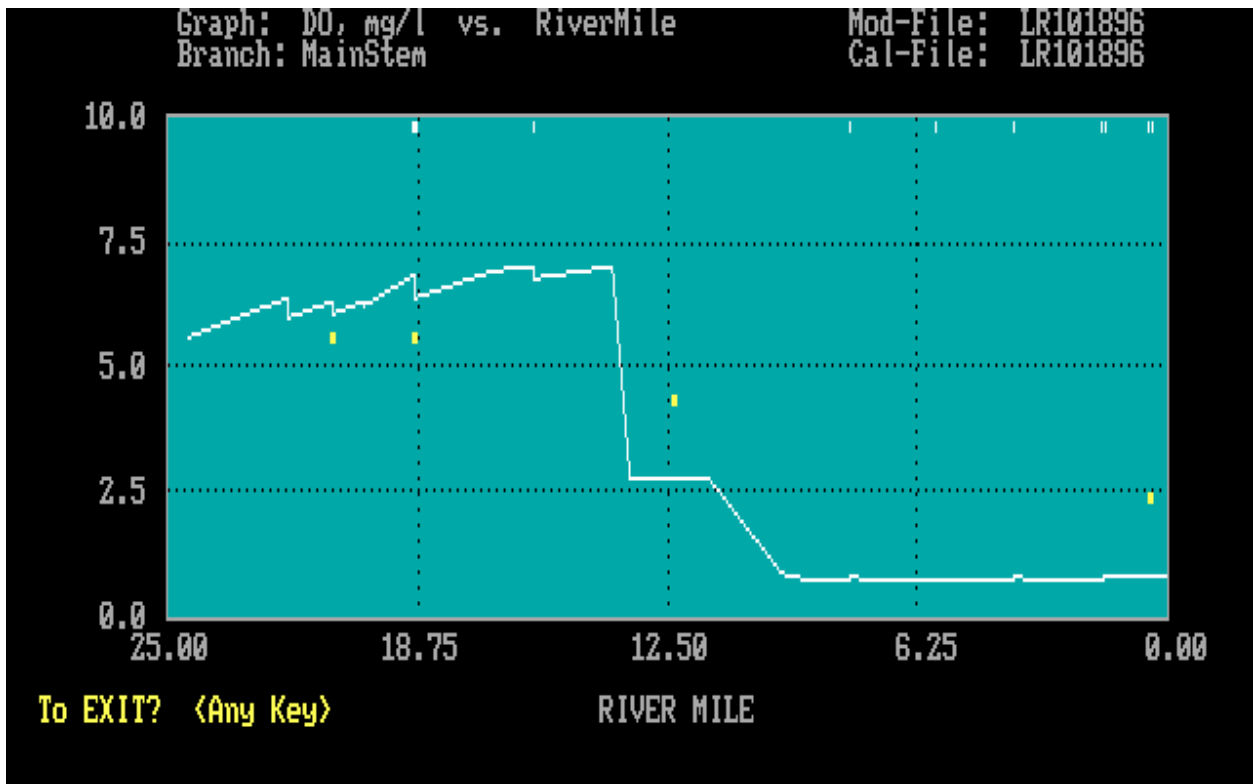


Figure 33. DoSag results from the validation on 10/18/1996.

### Validations in space

DoSag was spatially validated on the Piscola Creek watershed. Both the Little River and the Piscola Creek are listed on the 303(d) list as DO impaired (EPD, 2002). The Piscola Creek watershed lies south of the LREW near the Georgia-Florida border (Figure 34). Both watersheds are located in the Tifton Upland ecoregion (in the EPA's ecoregion level IV classification) of the coastal plain of Georgia (EPA, 2004). The EPA uses the concept of ecoregions to help categorize lands based on multiple environmental parameters. According to the EPA (2004);

“Ecoregions denote areas of general similarity in ecosystems and in the type, quality, and quantity of environmental resources. They are designed to serve as a special framework for research, assessment, management, and monitoring of ecosystems and ecosystem components.”

So, the location of both watersheds in one ecoregion signifies that they are similar to each other. But, the extent to which these similarities extend is not fully quantified.

Differences between the two watersheds were also investigated. The Piscola Creek watershed is slightly larger than the LREW at 390 km<sup>2</sup> versus 334 km<sup>2</sup>. The change in elevation in the Piscola Creek watershed is 54 m versus 45 m in the LREW. United States Geological Society (USGS) land use maps of the Piscola Creek watershed show it to be mostly agriculture and forest. Land use in the LREW is mostly agricultural with significant amounts of forested and wetland areas.

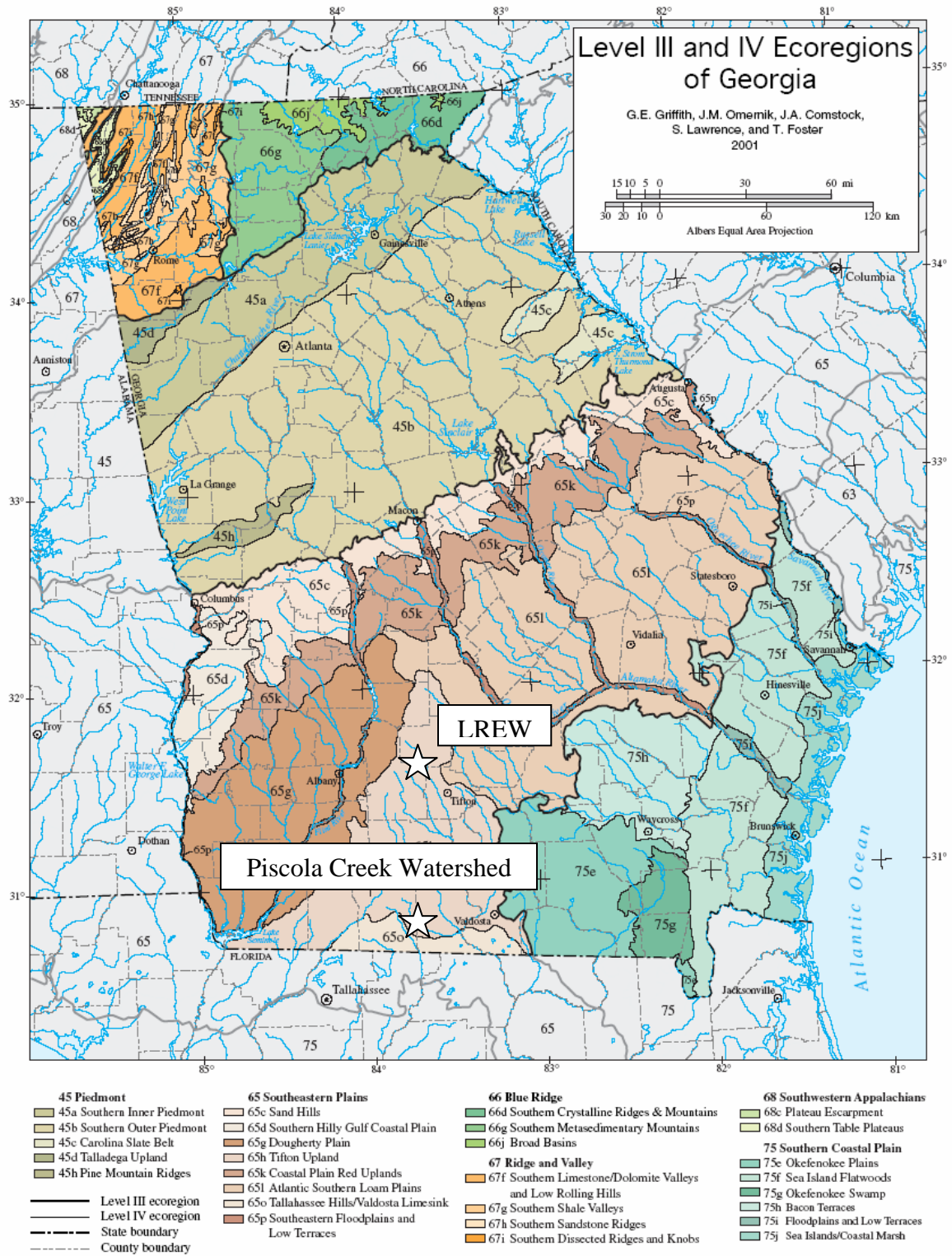


Figure 34. The ecoregions of Georgia. (Reproduced from the EPA's website. EPA, 2004)

The Piscola Creek watershed was subdivided into 26 subbasins (Figure 35). This skeletonization included the mainstem and two subbranches. Water quality samples were not collected in the Piscola creek watershed on the same day as on the calibration day. So, the validation of DoSag on the Piscola Creek watershed was conducted on the two Piscola sampling days that surrounded the calibration date in the LREW. The two sampling dates that were the closest to March 12, 2004 were March 9<sup>th</sup>, 2004 and March 16<sup>th</sup>, 2004. Parameters that were sampled in Piscola Creek included DO, water temperature, and flow. These parameters were measured by the University of Georgia and SEWRL in the same manner that they were measured in the LREW. The water quality and flow data collected from the two sites on the mainstem were averaged together for representation in the model.

The sampled water temperature, DO, and flow for the spatial validations were measured in the Piscola Creek. The rest of the data used in the spatial validations came from the LREW calibration. Velocity was assumed constant and was represented by the average velocity in the LREW on the calibration day. A value of  $0.067 \text{ m s}^{-1}$  was used throughout the watershed. Depth was also assumed constant. A value of 0.34 m was used throughout the watershed which was the average depth in the LREW on the calibration day. The water yield was found by dividing flow at the end of the reach by the entire watershed area and so the water yield was a constant as well. SOD was assumed to be  $6 \text{ g m}^{-2} \text{ d}^{-1}$ . This is the same value that was used on all of the calibration and validation runs in the LREW. Net photosynthesis was input as  $1.5 \text{ mg L}^{-1} \text{ d}^{-1}$ . This value was the same value used to represent net photosynthesis in the LREW on the calibration date. DO saturation of lateral flow was input as the average of DO at the two

stations on the mainstem. The O'Connor Dobbins equation was used to calculate reaeration in all of the reaches. The model outputs of these two spatial validations are shown in Figures 36 and 37. The comparatively linear nature of both of these lines is due to the fact that many parameters were input as constants.

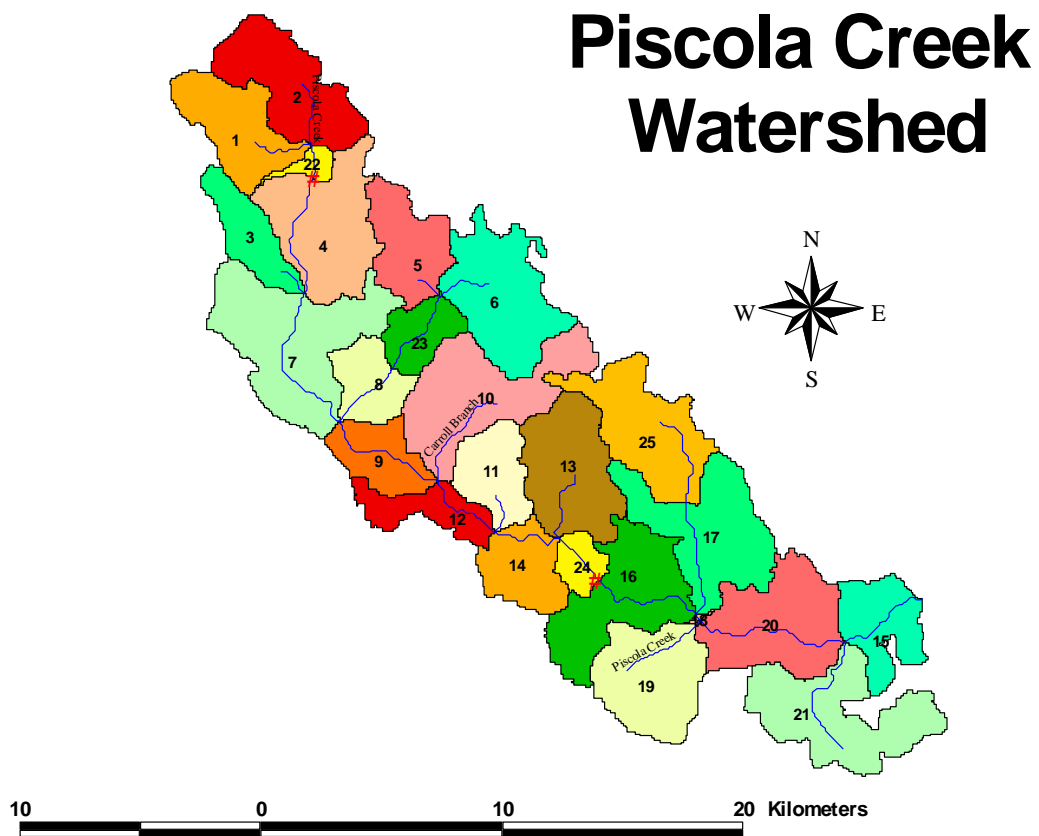


Figure 35. Piscola Creek watershed skeletonization.

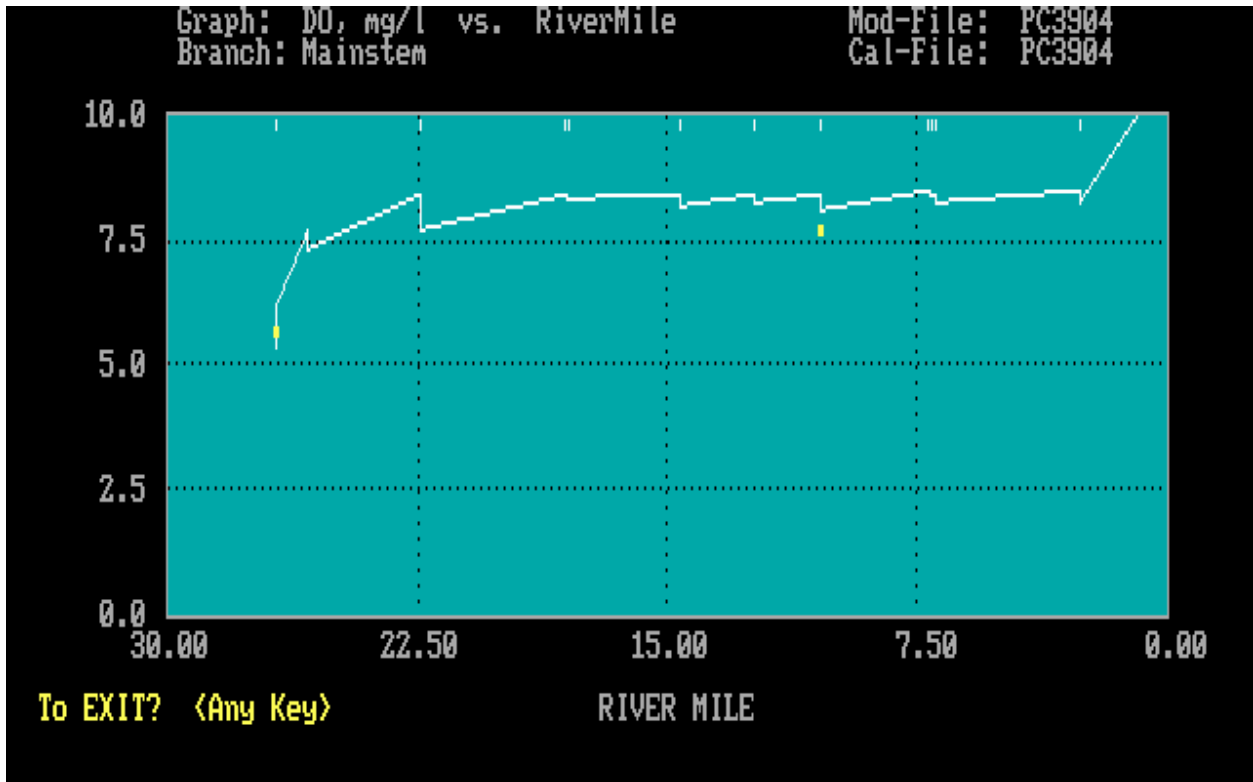


Figure 36. Validation at the Piscola Creek watershed on March 9<sup>th</sup>, 2004

Validation error

The measurement of how closely the modeled and sampled DO data matched was conducted by computing true error. Error was calculated at each of the sampling stations in both the LREW and the Piscola Creek watershed.

An overview of the parameters and errors from each of the modeling scenarios is shown in Table 10. In this table, error is represented as the absolute value of the true error of sampled versus modeled DO, averaged between all of the gauging stations. The scenarios in the table were ranked according to error. As an exception to this rule, the calibration date was listed first to facilitate comparison. Average absolute error ranged from 0.57 to 2.56 mg L<sup>-1</sup>. Note that the scenario that demonstrated the least

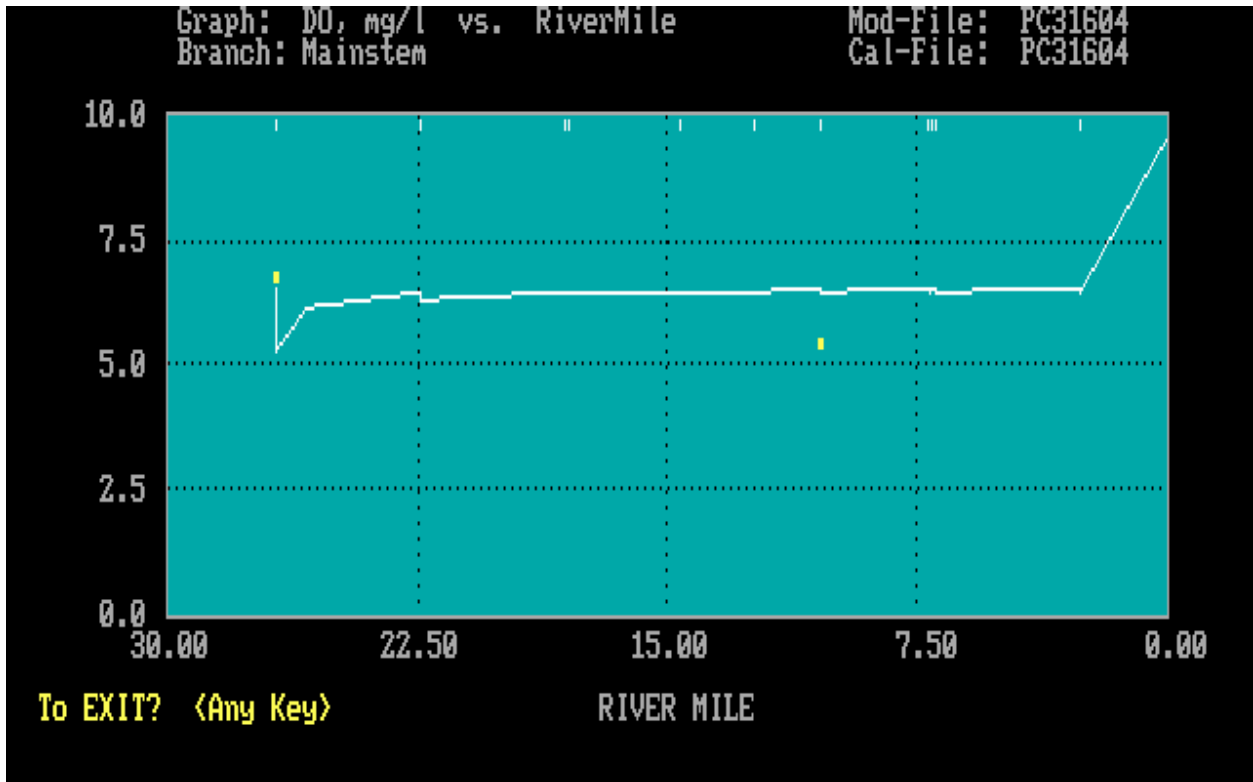


Figure 37. Validation at the Piscola Creek watershed on March 16<sup>th</sup>, 2004.

amount of error was the validation run in Piscola Creek. This was a validation in space, not in time. This scenario shows even less error than the calibration date. When considering the error in the Piscola Creek watershed, it should be recognized that only two DO samples were taken on the mainstem of the Piscola Creek compared to five DO samples on the mainstem of the LREW. On the other end of the spectrum, the scenario with the greatest average error was a temporal validation on September 9<sup>th</sup>, 1994. At station B this scenario had the hottest temperature and the second to the lowest flow that was modeled.

Table 10. Selected parameter values for each validation run ordered by DO error.

<b>Date</b>	<b>Location</b>	<b>Water temp (°C)</b>	<b>Flow (L s<sup>-1</sup>)</b>	<b>Sampled DO (mg L<sup>-1</sup>)</b>	<b>Absolute value of true error of DO averaged between all gauging stations (mg L<sup>-1</sup>)</b>
<b>3/12/2004</b>	<i>LREW**</i>	12.7	1394	6.6	0.91
<b>3/9/2004</b>	Piscola*	12.2	4300*	7.7	0.57
<b>4/24/1996</b>	LREW**	17.7	1218	3.9	0.84
<b>4/22/1993</b>	LREW**	16.3	1008	5.0	1.03
<b>4/18/1996</b>	LREW**	20.8	2756	4.1	1.06
<b>10/18/1996</b>	LREW**	20.2	890	2.3	1.22
<b>3/16/2004</b>	Piscola*	18.2	3500	6.5	1.25
<b>5/9/1996</b>	LREW**	24.0	1246	3.1	2.10
<b>5/12/1997</b>	LREW**	17.8	155	2.8	2.23
<b>9/2/1994</b>	LREW**	27.5	574	2.6	2.56

\* Average of sampled values in Piscola Creek Watershed for all Piscola Creek entries.

\*\*Data from station B for all LREW watersheds.

## Chapter 7: Summary and Conclusions

### Parameter estimation

Several conclusions can be drawn from the various investigations into parameter estimation. The Dobbins O'Connor equation was shown to represent the system more accurately than the Tsivoglou equation. The chlorophyll *a* equation was capable of predicting levels of net photosynthesis as these numbers approximated the numbers calculated by the diurnal equation and demonstrated the expected seasonal trends. The calibrated value for SOD fell within the published ranges for SOD. The groundwater measured in shallow wells was anoxic to hypoxic.

### Errors associated with low flow and high temperatures

The absolute value of the true error, averaged between all of the gauging stations, under all of the modeled conditions ranged between 0.57 and 2.56 mg L<sup>-1</sup> of DO. DoSag was capable of modeling low levels of DO. However, larger modeling errors were associated with low flow and high temperatures (Table 10). The scenario that demonstrated the largest average error was also the scenario with the highest temperature. The scenario that demonstrated the second highest average error was the scenario with the lowest flow. Although it was expected that low flow and low velocity scenarios would be associated with large errors, it was surprising that high temperatures were associated with large errors. This may be because temperature was a variable in several parameters including, DO saturation, SOD, BOD and net

photosynthesis. The errors inherent in equations that correct for temperature, such as the Arrhenius Equation, may have worked to compound the errors in the final model output.

#### *Dissolved oxygen in the upper and lower reaches*

Generally, DO dropped in the downstream direction in the LREW. When compared to the lower reaches in the LREW, the upper reaches showed steeper channel gradients, more channelized streams, and higher velocities. As a result, higher DO concentrations were expected in these upper reaches. However, in almost all of the modeling scenarios, this trend was magnified and the DO concentrations were modeled as being too high in the upper reaches and too low in the lower reaches. Several investigations into resolving this magnification were conducted including increasing net photosynthesis in the downstream direction, decreasing SOD in the downstream direction, altering the skeletonization of the model based on visual assessments at stream crossings, and tuning the percent saturation of lateral flow. None of these parameters proved to be satisfactorily capable of resolving the discrepancy.

Reaeration proved to be a very sensitive parameter in the calibrated model. Reaeration, as computed by the O'Connor Dobbins equation, is based on the diffusivity of oxygen in water, water depth, and velocity. Reaeration increases with increasing velocity and decreases with increasing depth. Higher velocities were recorded in the upper reaches. Very low velocities were recorded in the lower reaches. Stream depth stayed relatively stable throughout the watershed. Thus, reaeration decreased in the downstream direction. But the model magnified the downstream decrease in DO that was actually occurring in the system. This may be due to how reaeration was

calculated. An investigation into the reaeration processes particular to coastal plain streams during low velocity conditions needs to be conducted to better understand reaeration in the LREW. This would result in a much better understanding of the actual physical processes occurring in the stream.

A value for SOD was input into the model based on literature values. However, there was a wide range of literature values, even for blackwater streams. So, a specific number had to be chosen from this range. SOD was assumed to be the oxygen demand that was left after all of the 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. So, the value used for SOD may or may not represent the physical processes actually occurring in the stream. Therefore, a better understanding of SOD could also result in a better understanding of reaeration. SOD is currently being measured in the LREW by Crompton et al. (2005). These values will be available for future modeling efforts.

The spatial validation on the Piscola Creek watershed did not demonstrate the magnified drop in DO in the downstream direction. The DO in this watershed remained relatively steady between the two sampling stations on the mainstem and represented the sampled DO fairly well. Velocity and depth were input as constants in these modeling scenarios. Because of this, DoSag calculated reaeration as a constant throughout the reaches. Net photosynthesis, BOD, SOD, and the percent saturation of lateral flow were also input as constants. All of these constant parameter inputs resulted in a relatively constant level of DO throughout the mainstem.

### Negative dissolved oxygen concentrations

DO in the DoSag model can drop well below 0 mg L<sup>-1</sup>. In one of the scenarios, DO dropped as low as -11.4 mg L<sup>-1</sup>. It is physically impossible to have such a negative concentration of dissolved oxygen. When DO falls to a negative number in DoSag the water must pass back through those negative values on its way to having a positive concentration. So, water with a DO deficit requires more oxygen to reaerate to a positive value than water with a zero concentration of DO. And as a result, reaches with negative values of DO have a more difficult time getting back up to the TMDL standard for DO.

Modifying the model in a way that prevents negative concentrations appears necessary. Two easy solutions to this problem exist. The first solution involves calculating SOD based on a differential equation that is dependant upon the concentration of oxygen in the water. The second solution involves using an "if then" statement to halt SOD when DO goes to zero. An investigation into SOD at very low levels of DO should be conducted to determine which method is most suitable.

The negative DO concentration is not an issue in streams with continuously high levels of DO. But, in areas like the coastal plain of Georgia where waters are regularly hypoxic or anoxic negative concentrations of DO will impact the validity of the model results.

### Anthropogenic impacts on dissolved oxygen

The 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 as to whether

DoSag is appropriate for establishing DO TMDLs on streams segments without point sources. To answer this question, the following exercise was performed. 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  $0.3 \text{ mg L}^{-1}$  at the end of the model. Considering the fact that DO in the LREW regularly falls well below  $4.0 \text{ mg L}^{-1}$ , 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 modeled SOD value may not correspond to the value in the real system. SOD must first be properly quantified if the question of natural levels of DO is to be properly addressed. If the modeled SOD value of  $6 \text{ g m}^{-2} \text{ d}^{-1}$  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  $6 \text{ g m}^{-2} \text{ d}^{-1}$  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 in the newly calibrated model after removing all sources of BOD 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 a reference stream with minimal anthropogenic impacts. The model should first be calibrated in the reference watershed. Using the calibrated parameters, which

may be anthropogenically impacted, from the reference watershed the model should be rerun in an impaired watershed. Parameters, which may be anthropogenically impacted, include BOD, SOD, net photosynthesis and temperature. The model output from the impaired watershed, using the reference stream parameters, can then 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. When a stream is nutrient limited, 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 in DoSag 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 yet be fully understood through modeling.

#### Acceptable error for TMDLs

There will always be error when modeling a system as complicated as the water quality in a watershed. The level of applicability that the model has to the TMDL program depends on the amount of error that is acceptable to regulatory agencies. DoSag can be useful when looking at trends and changes in the LREW. However, DoSag cannot represent specific dates or locations accurately enough to be used as a predictor of DO.

#### Using the calibrated model in other locations

The EPD (1999) stated that natural levels of DO may be understood through the application of mathematical models. The calibration of a model is time consuming. The calibrated model was spatially validated in the Piscola Creek watershed to determine if DoSag could represent various 303(d) listed streams in the coastal plain without being recalibrated. This attempt was successful and the errors that the model showed in these validations were less than the errors associated with high temperatures and low flows. Both the LREW and the Piscola Creek watershed are located in the Tifton Upland ecoregion. The next step to understanding how well the calibrated model can represent other watersheds is to validate it in another watershed in the coastal plain but not in the Tifton Upland. If the new spatial validation demonstrates acceptable errors for

regulatory purposes then the model should be acceptable for use in other watersheds with similar characteristics without being recalibrated. Using the calibrated model in other locations will not only help the TMDL process operationally, it may also indicate how similar these streams are to each other.

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## **Appendix A: Abbreviations**

ARS - Agricultural Resource Service

ASCE - American Society of Civil Engineers

APHA - American Public Health Association

BOD - Biochemical oxygen demand

BOD<sub>k</sub> - Bxidation rate of biochemical oxygen demanding substances

CBOD - Carbonaceous biochemical oxygen demand

CBOD<sub>u</sub> - Ultimate carbonaceous biochemical oxygen demand

DEM - Digital elevation map

DNR - Department of Natural Resources

DO - Dissolved oxygen

EPA - Environmental Protection Agency

EPD - Environmental Protection Division

LREW - Little River Experimental Watershed

NBOD - Nitrogenous biochemical oxygen demand

NBOD<sub>u</sub> - Ultimate nitrogenous biochemical oxygen demand

NPDES - National Pollution Discharge Elimination System

SEWRL - Southeast Watershed Research Laboratory

SOD - Sediment oxygen demand

uBOD – ultimate BOD

USDA - United States Department of Agriculture

USGS - United States Geological Survey

YSI - Yellow Springs Instruments

## Appendix B: Modeling Data

DATE	GAGE	Flow (m <sup>3</sup> s <sup>-1</sup> )	Depth (m)	velocity (ms <sup>-1</sup> )	Temp (°C)	DO (mgL <sup>-1</sup> )	Production Factor (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Net Photosynthesis (mgL <sup>-1</sup> d <sup>-1</sup> )
3/12/2004	STAM	0.015			12.23	3.29	0.006	1.5
3/12/2004	STAK	0.181	0.05	0.543	11.91	7.6	0.011	
3/12/2004	STAJ	0.093	0.38	0.067	12.41	7.03	0.004	
3/12/2004	STAI	0.217	0.28	0.162	11.64	7.51	-0.005	
3/12/2004	STAF	0.560	0.23	0.022	11.71	7.49	0.005	
3/12/2004	STAN	0.140			11.89	7.64	0.009	
3/12/2004	STAO	0.097	0.57	0.031	12.86	8.18	0.006	
3/12/2004	STAB	1.394	0.44	0.018	12.7	6.6	0.004	
3/12/2004	STAO3				16	9.13	0.000	

DATE	GAGE	Flow (m <sup>3</sup> s <sup>-1</sup> )	Depth (m)	velocity (ms <sup>-1</sup> )	Temp (°C)	DO (mgL <sup>-1</sup> )	Production Factor (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Net Photosynthesis (mgL <sup>-1</sup> d <sup>-1</sup> )
4/24/1996	STAM						0.006	1.5
4/24/1996	STAK	0.096	0.04	0.448	18.75	7.47	0.006	
4/24/1996	STAJ	0.082	0.36	0.128	19.22	6.9	0.004	
4/24/1996	STAI	0.348	0.29	0.140	18.59	5.8	0.015	
4/24/1996	STAF	0.666	0.24	0.025	18.8	6.56	0.005	
4/24/1996	STAN						0.002	
4/24/1996	STAO3							
4/24/1996	STAO	0.141	0.62	0.056	17.25	6.77	0.009	
4/24/1996	STAB	1.218	0.42	0.016	17.71	3.93	0.002	

DATE	GAGE	Flow (m <sup>3</sup> s <sup>-1</sup> )	Depth (m)	velocity (ms <sup>-1</sup> )	Temp (°C)	DO (mgL <sup>-1</sup> )	Production Factor (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Net Photosynthesis (mgL <sup>-1</sup> d <sup>-1</sup> )
4/18/1996	STAM							1.5
4/18/1996	STAK	0.220	0.07	0.521	16.63	6.6	0.013	
4/18/1996	STAJ	0.198	0.36	0.128	16.71	6.4	0.009	
4/18/1996	STAI	0.667	0.32	0.113	17.67	6.4	0.013	
4/18/1996	STAF	1.270	0.31	0.037	18.46	5.88	0.011	
4/18/1996	STAN							
4/18/1996	STAO3							
4/18/1996	STAO	0.117	0.58	0.037	21.8	5.89	0.007	
4/18/1996	STAB	2.756	0.55	0.028	20.81	4.1	0.008	

DATE	GAGE	Flow (m <sup>3</sup> s <sup>-1</sup> )	Depth (m)	velocity (ms <sup>-1</sup> )	Temp (°C)	DO (mgL <sup>-1</sup> )	Production Factor (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Net Photosynthesis (mgL <sup>-1</sup> d <sup>-1</sup> )
5/12/1997	STAM				17.18	5.57	0.297	1.7
5/12/1997	STAK	0.002			17.18	5.57	0.175	
5/12/1997	STAJ	0.007	0.32	0.006	16.16	6.43	0.124	
5/12/1997	STAI	0.024	0.27	0.241	16.57	5.05	0.145	
5/12/1997	STAF	0.108	0.13	0.009	17.84	5.01	0.172	
5/12/1997	STAN		0.51	0.007	18.45	5.94	0.282	
5/12/1997	STAO3		0.51	0.007	18.45	5.94	0.282	
5/12/1997	STAO	0.018	0.51	0.007	18.45	5.94	0.393	
5/12/1997	STAB	0.155	0.23	0.007	17.76	2.76	0.169	

DATE	GAGE	Flow (m <sup>3</sup> s <sup>-1</sup> )	Depth (m)	velocity (ms <sup>-1</sup> )	Temp (°C)	DO (mgL <sup>-1</sup> )	Production Factor (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Net Photosynthesis (mgL <sup>-1</sup> d <sup>-1</sup> )
9/2/1994	STAM				24.35	5.96	0.092	1.5
9/2/1994	STAK	0.023	0.01	7.382	24.35	5.96	0.092	
9/2/1994	STAJ	0.015	0.34	0.012	23.71	6.07	0.293	
9/2/1994	STAI	0.125	0.26	0.186	25.78	5.5	0.049	
9/2/1994	STAF	0.262	0.13	0.011	26.01	4.35	0.127	
9/2/1994	STAN		0.50	0.006	26.96	6.16	0.355	
9/2/1994	STAO3		0.50	0.006	26.96	6.16	0.355	
9/2/1994	STAO	0.016	0.50	0.006	26.96	6.16	0.355	
9/2/1994	STAB	0.574	0.33	0.009	27.46	2.56	0.115	

DATE	GAGE	Flow (m <sup>3</sup> s <sup>-1</sup> )	Depth (m)	velocity (ms <sup>-1</sup> )	Temp (°C)	DO (mgL <sup>-1</sup> )	Production Factor (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Net Photosynthesis (mgL <sup>-1</sup> d <sup>-1</sup> )
4/22/1993	STAM				13.6	8.99	0.204	1.5
4/22/1993	STAK	0.096	0.04	0.600	13.6	8.99	0.204	
4/22/1993	STAJ	0.087	0.37	0.064	14.09	8.31	0.171	
4/22/1993	STAI	0.304	0.30	0.146	14.28	8.45	0.272	
4/22/1993	STAF	0.593	0.15	0.013	15.02	7.63	0.338	
4/22/1993	STAN		0.52	0.009	14.84	8.47	0.358	
4/22/1993	STAO3		0.52	0.009	14.84	8.47	0.358	
4/22/1993	STAO	0.025	0.52	0.009	14.84	8.47	0.358	
4/22/1993	STAB	1.008	0.40	0.014	16.33	5.02	0.240	

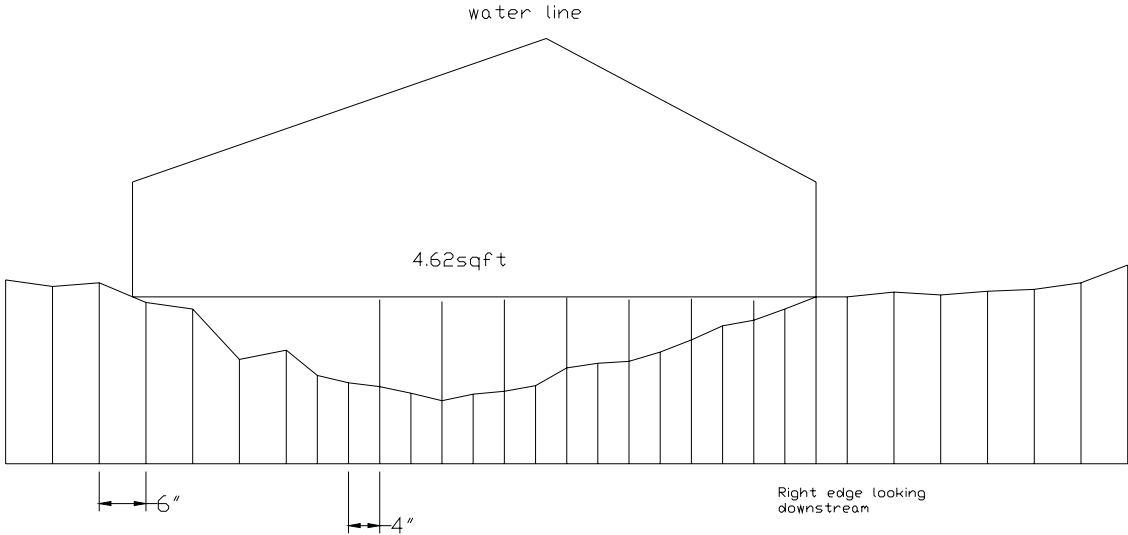
DATE	GAGE	Flow (m <sup>3</sup> s <sup>-1</sup> )	Depth (m)	velocity (ms <sup>-1</sup> )	Temp (°C)	DO (mgL <sup>-1</sup> )	Production Factor (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Net Photosynthesis (mgL <sup>-1</sup> d <sup>-1</sup> )
10/18/1996	STAM				18.58	5.56	0.076	1.3
10/18/1996	STAK	0.202	0.06	0.524	18.58	5.56	0.076	
10/18/1996	STAJ	0.207	0.40	0.104	18.8	5.35	0.060	
10/18/1996	STAI	0.588	0.31	0.119	18.55	5.61	0.105	
10/18/1996	STAF	0.723	0.13	0.009	21.5	4.32	0.091	
10/18/1996	STAN		0.54	0.017	20.66	4.64	0.027	
10/18/1996	STAO3		0.54	0.017	20.66	4.64	0.027	
10/18/1996	STAO	0.051	0.54	0.017	20.66	4.64	0.027	
10/18/1996	STAB	0.890	0.38	0.013	20.22	2.34	0.061	

DATE	GAGE	Flow (m <sup>3</sup> s <sup>-1</sup> )	Depth (m)	velocity (ms <sup>-1</sup> )	Temp (°C)	DO (mgL <sup>-1</sup> )	Production Factor (m <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup> )	Net Photosynthesis (mgL <sup>-1</sup> d <sup>-1</sup> )
5/9/1996	STAM							1.7
5/9/1996	STAK	0.049	0.02	0.954	22.01	5.02	0.039	
5/9/1996	STAJ	0.031	0.36	0.024	21.73	5.73	0.025	
5/9/1996	STAI	0.183	0.28	0.162	22.8	5.17	0.036	
5/9/1996	STAF	0.479	0.23	0.023	24.25	4.37	0.026	
5/9/1996	STAN		0.57	0.031				
5/9/1996	STAO3		0.57	0.031				
5/9/1996	STAO	0.101	0.57	0.031	27.27	6.68	0.030	
5/9/1996	STAB	1.246	0.42	0.016	4	3.1	0.042	

**Appendix C: Cross-Sections**

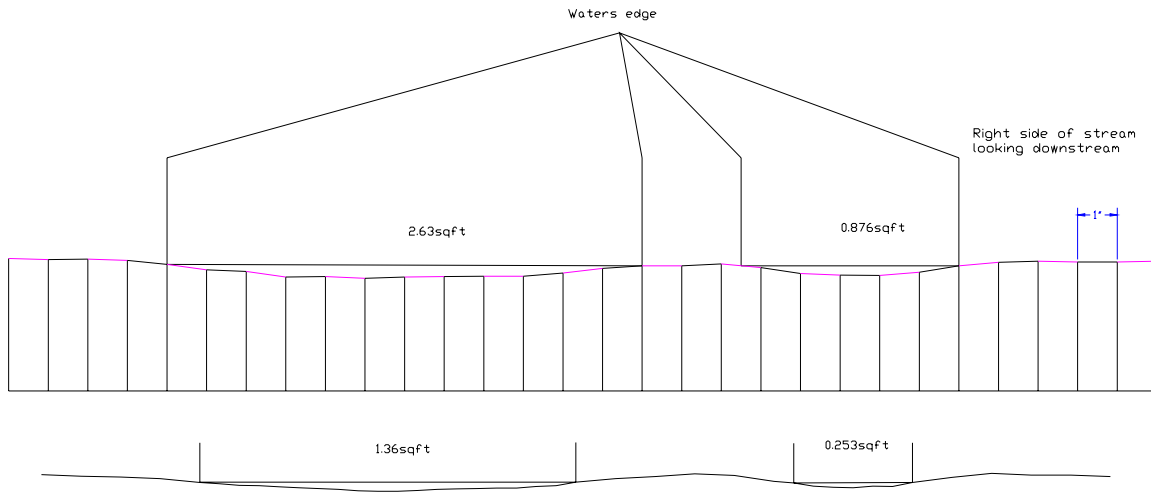
Station M

Upstream from bridge  
Just downstream from small incoming trib  
3-18-04 at 10:00



Station M

Station K  
50 yards upstream  
from bridge  
3-19-04 at 9:30

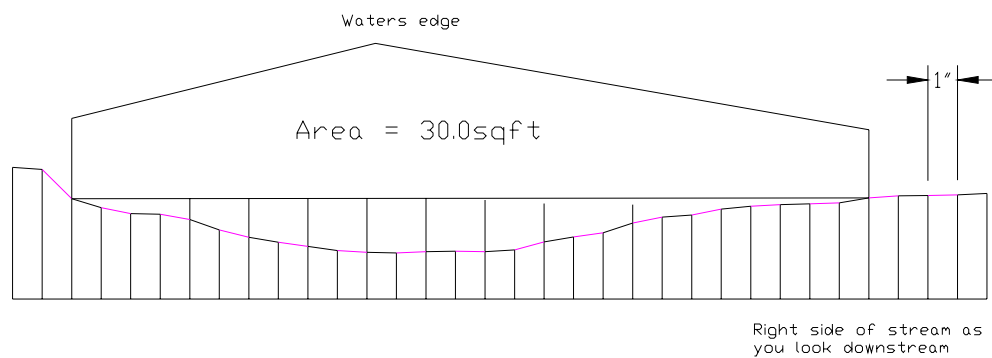


Station K  
50 yards upstream  
from bridge (same  
site as above)  
5-12-04 at 11:30

Station K

Cross Section of Station I

50 yards upstream from bridge crossing and weir  
3-19-04 at 10:15

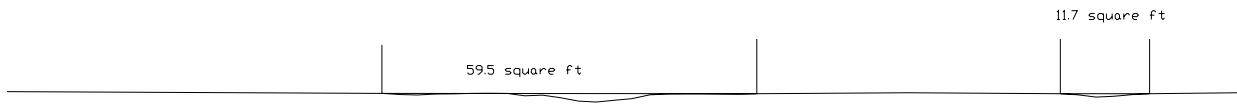


Station I

Station F

Upstream from bridge  
5-12-04 at 10:00

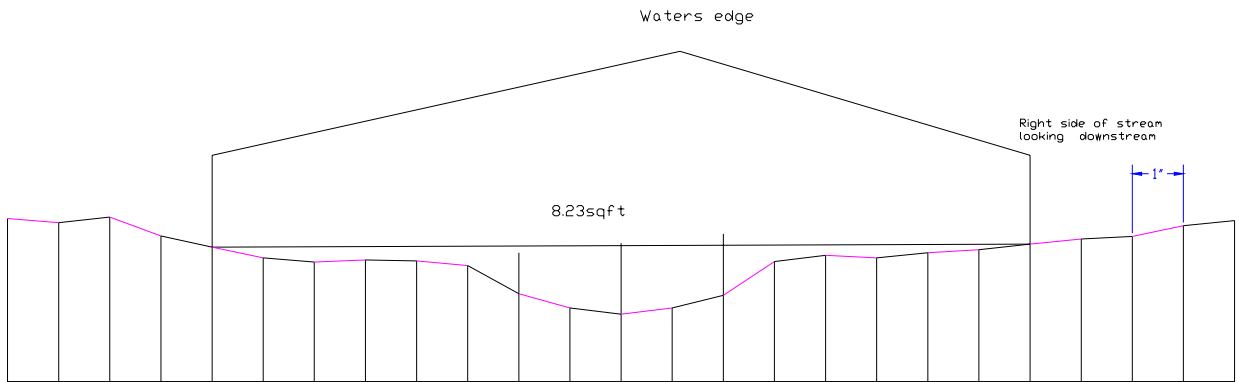
area at the time = 71.2sqft



Station F

Station N

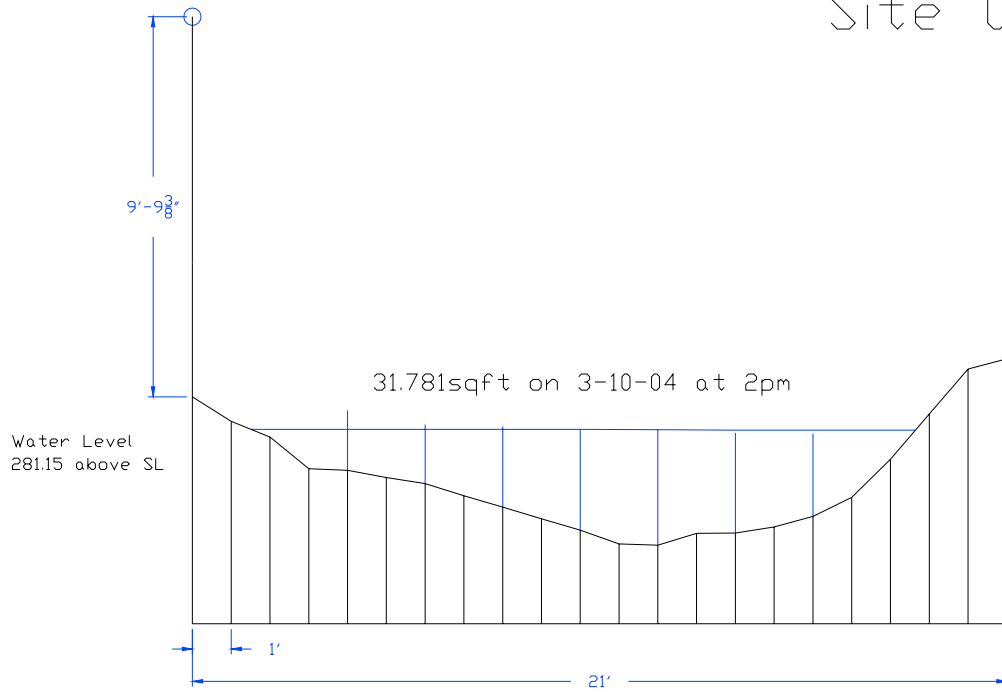
250 yards upstream from bridge  
3-19-04 at 11:45



Station N

Benchmark at 288.675 Feet above MSL

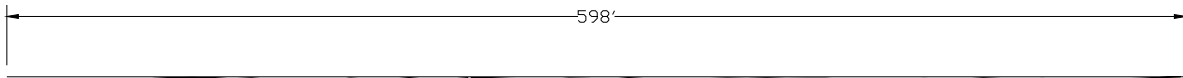
Site 0



Station O

Station B

Upstream from bridge  
3-29-04 at 2:30  
Measurements taken every 10ft  
area at the time = 514sqft



Station B

## Appendix D: DoSag Calibration Model Inputs

\* \* \* SYSTEM DATA AND SELECTED RUN PARAMETERS \* \* \*

=====

PROJ: LR\_4-18-96\_Cal1          Reaches    = 31   Ints = 0  
 Date: 11-19-2004..... Branches    = 3   Wtfs = 0  
 File: LR31204..... Sub-Branches = 0   Dams = 0

SOD Variable:    ON.   Net P/R Variable: ON.  
 Substance No. 1: OFF --> TNH3 expressed in mg/l  
 Substance No. 2: OFF --> Sub#2 expressed in ---

Georgia Soil Type --> No. 2: Southern Coastal Plain  
 Soil Vel Eqn = 0.181\*(Q^ 0.190)\*(S^ 0.000)\*(A^ 0.000)\*(L^ 0.219)

=====

Calibration of Little River Model  
 Data from 3-12-2004  
 4-21-04  
 Before SOD and CBODk measured data

\* \* \* BRANCH OPTIONS AND SELECTED HEADWATER DATA \* \* \*

=====

\*\*\*\*\* BRANCH DESCRIPTIONS \*\*\*\*\* <---- CALC OPTIONS ---->

No.	Type	Name	Depth	Vel	Reaer
1	MAIN STEM	MainStem.....	ON	Soil Eq	O'Connor
2	BRANCH	J Stem.....	ON	Soil Eq	O'Connor
3	BRANCH	N Stem.....	ON	Soil Eq	O'Connor
4	BRANCH	O Stem.....	ON	Soil Eq	O'Connor

=====

```

=====
BRAN ***** HEADWATER GEOMETRY ***** <----- FLOW PARAMETERS ----->
No. Rch RivMile Elev drAREA Fixed Opt Prod Used
=====
1 1 24.53 150.5 1.010 0.00 CALC 0.526 0.53
2 28 19.85 82.0 8.525 0.00 CALC 0.380 3.24
3 29 3.28 12.8 5.773 0.00 CALC 0.820 4.73
4 30 4.07 49.2 1.572 0.00 CALC 0.560 0.88
=====

```

Calibration of Little River Model  
Data from 3-12-2004  
4-21-04  
Before SOD and CBODk measured data

\*\*\* HEADWATERS DATA AND SELECTED BRANCH RESULTS \*\*\*

```

=====
BRAN CBODu NBODu <----- DO PARAMETERS -----> TNH3 Sub#2
No. mg/l mg/l Fixed Opt %Sat DoSat Used mg/l ---
=====
1 6.0 0.5 3.3 INPUT 0.0 10.66 3.29 0.0 0.000E+00
2 16.0 1.3 7.0 INPUT 0.0 10.65 7.03 0.0 0.000E+00
3 16.0 1.3 7.6 INPUT 0.0 10.80 7.64 0.0 0.000E+00
4 18.0 1.3 9.1 INPUT 0.0 9.85 9.13 0.0 0.000E+00
=====

```

```

=====
BRANCH hwTEMP ***** END-OF-BRANCH RESULTS *****
No. degC Reach RivMile Elev SumArea SumFlow SumTOT
=====
1 12.2 EOM 0.00 0.0 129.055 55.70 16.233
2 12.4 5 18.82 68.9 9.075 3.46 0.119
3 11.9 24 1.57 9.8 8.973 7.36 1.020
=====

```

4 16.0 26 0.38 0.0 6.972 3.90 2.163

=====  
 Calibration of Little River Model  
 Data from 3-12-2004  
 4-21-04  
 Before SOD and CBODk measured data

\*\*\* MODEL REACH STRUCTURE \*\*\*

11-21-2004 9:02 pm

=====  
 RCH RIVER ELEV REACH REACH DESCRIPTION  
 # Mile ft Type  
 =====

-(br 1) MAIN STEM: MainStem

1	24.53	150.5	stream	Reach Description No. 1.....
2	22.04	111.5	stream	Reach Description No. 2.....
3	20.90	91.8	stream	Reach Description No. 3.....
4	20.09	78.7	stream	Reach Description No. 4.....
5	18.82	68.9	Branch	Reach Description No. 5.....
6	18.82	68.9	-trib-	Reach Description No. 6.....
7	18.82	68.9	stream	Reach Description No. 7.....
8	16.84	59.0	stream	Reach Description No. 8.....
9	15.86	59.0	-trib-	Reach Description No. 9.....
10	15.86	59.0	stream	Reach Description No. 10.....
11	13.91	49.2	stream	Reach Description No. 11.....
12	12.32	39.4	stream	Reach Description No. 12.....
13	11.44	39.4	stream	Reach Description No. 13.....
14	9.63	29.5	stream	Reach Description No. 14.....
15	8.88	29.5	stream	Reach Description No. 15.....
16	7.93	26.2	-trib-	Reach Description No. 16.....
17	7.93	26.2	stream	Reach Description No. 17.....
18	6.94	19.7	stream	Reach Description No. 18.....
19	5.79	9.8	-trib-	Reach Description No. 19.....
20	5.79	9.8	stream	Reach Description No. 20.....
21	3.83	9.8	-trib-	Reach Description No. 21.....
22	3.83	9.8	stream	Reach Description No. 22.....
23	2.65	9.8	stream	Inserted Reach (was No 23).....
24	1.57	9.8	Branch	Reach Description No. 23.....
25	1.57	9.8	stream	Inserted Reach (was No 25).....
26	0.38	0.0	Branch	Reach Description No. 24.....
27	0.38	0.0	stream	Inserted Reach (was No 27).....

```

-(br 2) BRANCH: J Stem
28 19.85 82.0          stream      Reach Description No. 25.....

-(br 3) BRANCH: N Stem
29 3.28 12.8          stream      Reach Description No. 26.....

-(br 4) BRANCH: O Stem
30 4.07 49.2          stream      Reach Description No. 27.....
31 1.69 19.7          stream      Reach Description No. 28.....

```

```

=====
DS = 0.00 0.0 ---- DISCHARGES 0; INTAKES 0; DAMS 0
RiverMiles and Elevations represent 'Head-of-Reach' Values.
Model File Name: LR31204

```

Calibration of Little River Model  
 Data from 3-12-2004  
 4-21-04  
 Before SOD and CBODk measured data

```

*** STREAM DEPTH & REACH PHYSICAL DATA ***
11-21-2004                                9:02 pm
=====
RCH LENGTH dELEV SLOPE drAREA <---- DEPTH PARAMETERS ---->
#  mi   ft   ft/mi  mi2  fixed coeff exp Opt-used
=====
-(br 1) MAIN STEM: MainStem
 1 2.494 39.00 15.638 1.618 1.2 0.000 0.000 | 1.2
 2 1.136 19.70 17.342 2.206 1.2 0.000 0.000 | 1.2
 3 0.814 13.12 16.118 2.015 1.2 0.000 0.000 | 1.2
 4 1.267 9.84 7.766 0.830 0.9 0.000 0.000 | 0.9
 5 Branch -- -- -- - -- -- -
 6 -trib- -- -- 2.781 - -- -- -
 7 1.984 9.84 4.960 1.209 0.9 0.000 0.000 | 0.9
 8 0.975 0.00 0.000 2.894 0.9 0.000 0.000 | 0.9
 9 -trib- -- -- 8.973 - -- -- -
10 1.954 9.84 5.036 5.290 0.9 0.000 0.000 | 0.9
11 1.588 9.84 6.196 3.678 0.8 0.000 0.000 | 0.8
12 0.880 0.00 0.000 3.224 0.8 0.000 0.000 | 0.8
13 1.806 9.84 5.449 1.689 1.5 0.000 0.000 | 1.5
14 0.754 0.00 0.000 2.344 1.5 0.000 0.000 | 1.5
15 0.951 3.28 3.449 1.373 1.5 0.000 0.000 | 1.5
16 -trib- -- -- 32.689 - -- -- -

```

```

17 0.989 6.56 6.633 1.368 1.5 0.000 0.000 | 1.5
18 1.153 9.84 8.534 0.972 1.5 0.000 0.000 | 1.5
19 -trib- -- -- 6.486 - -- -- -
20 1.954 0.00 0.000 2.473 1.5 0.000 0.000 | 1.5
21 -trib- -- -- 12.362 - -- -- -
22 1.186 0.00 0.000 2.879 1.5 0.000 0.000 | 1.5
23 1.075 0.00 0.000 1.139 1.5 0.000 0.000 | 1.5
24 Branch -- -- -- - -- -- -
25 1.194 9.84 8.241 1.921 1.5 0.000 0.000 | 1.5
26 Branch -- -- -- - -- -- -
27 0.378 0.00 0.000 0.612 1.5 0.000 0.000 | 1.5

```

-(br 2) BRANCH: J Stem

```

28 1.034 13.12 12.689 0.550 0.9 0.000 0.000 | 0.9

```

-(br 3) BRANCH: N Stem

```

29 1.706 3.00 1.758 3.200 1.9 0.000 0.000 | 1.9

```

-(br 4) BRANCH: O Stem

```

30 2.374 29.53 12.439 4.384 1.9 0.000 0.000 | 1.9
31 1.314 19.69 14.985 1.016 1.7 0.000 0.000 | 1.7

```

```

=====
SF = -- 1.00 1.00 1.00 -- --- --- 1.00

```

(\*) means Depth variable has been turned OFF for THAT Branch.

NOTE: 'used' - shows the Depth value 'used' in calculations.

'fixed' - identifies the Depth value fixed-by-user Input.

I or C - Depth 'used' is INPUT (I), or CALCULATED (C).

Model File Name: LR31204

Calibration of Little River Model

Data from 3-12-2004

4-21-04

Before SOD and CBODk measured data

\*\*\* REACH FLOW AND VELOCITY DATA \*\*\*

```

11-21-2004 9:02 pm

```

```

=====
RCH <---- FLOW PARAMETERS ----> <--- VELOCITY PARAMETERS --->
# fixed Prod Opt used fixed coeff exp Opt used
=====

```

-(br 1) MAIN STEM: MainStem

```

1 0.00 0.990 C 1.60 0.20 0.000 0.000 | 0.200

```

2	0.00	0.990	C	2.18	0.20	0.000	0.000		0.200
3	0.00	0.990	C	1.99	0.20	0.000	0.000		0.200
4	0.00	0.000	C	0.00	0.53	0.000	0.000		0.530
5	Branch	--	--	--	--	--	--	--	--
6	0.00	0.000	C	0.00	--	----trib----	--	--	--
7	0.00	0.480	C	0.58	0.53	0.000	0.000		0.530
8	0.00	0.480	C	1.39	0.53	0.000	0.000		0.530
9	0.00	0.480	C	4.31	--	----trib----	--	--	--
10	0.00	0.480	C	2.54	0.53	0.000	0.000		0.530
11	0.00	0.480	C	1.77	0.07	0.000	0.000		0.074
12	44.89	0.480	C	1.55	0.07	0.000	0.000		0.074
13	0.00	0.330	C	0.56	0.06	0.000	0.000		0.058
14	0.00	0.330	C	0.77	0.06	0.000	0.000		0.058
15	0.00	0.330	C	0.45	0.06	0.000	0.000		0.058
16	0.00	0.330	C	10.79	--	----trib----	--	--	--
17	0.00	0.330	C	0.45	0.06	0.000	0.000		0.058
18	0.00	0.330	C	0.32	0.06	0.000	0.000		0.058
19	0.00	0.330	C	2.14	--	----trib----	--	--	--
20	0.00	0.330	C	0.82	0.06	0.000	0.000		0.058
21	0.00	0.330	C	4.08	--	----trib----	--	--	--
22	0.00	0.330	C	0.95	0.06	0.000	0.000		0.058
23	0.00	0.330	C	0.38	0.06	0.000	0.000		0.058
24	Branch	--	--	--	--	--	--	--	--
25	0.00	0.330	C	0.63	0.06	0.000	0.000		0.058
26	Branch	--	--	--	--	--	--	--	--
27	0.00	0.330	C	0.20	0.06	0.000	0.000		0.058

-(br 2) BRANCH: J Stem

28	0.00	0.400	C	0.22	0.53	0.000	0.000		0.530
----	------	-------	---	------	------	-------	-------	--	-------

-(br 3) BRANCH: N Stem

29	0.00	0.820	C	2.62	0.10	0.000	0.000		0.102
----	------	-------	---	------	------	-------	-------	--	-------

-(br 4) BRANCH: O Stem

30	0.00	0.560	C	2.46	0.10	0.000	0.000		0.102
31	0.00	0.560	C	0.57	0.11	0.000	0.000		0.108

=====  
SF = --- 1.00      1.00 -- 1.00 1.00 1.00

NOTE: 'used' - shows the Value actually 'used' in calculations.

'fixed' - identifies the Value fixed-by-user Input.

I or C - Value 'used' is INPUT (I), or CALCULATED (C).

S or Q - Velocity from Soil (S), or  $V=c*Q^n$  (Q) equation.

Model File Name: LR31204

Calibration of Little River Model  
 Data from 3-12-2004  
 4-21-04  
 Before SOD and CBODk measured data

\* \* RATES: BOD, TNH3, Sub#2 (Base e @ 20 Deg.C) \* \*  
 11-21-2004 9:02 pm

```

=====
RCH TEMP Kr,CBOD Kd,CBOD Kd,NBOD Kx,TNH3 Kz,Sub#2
# degC /day /day /day /day /day
=====
-(br 1) MAIN STEM: MainStem
1 11.9 0.040 0.040 0.130 0.000 0.000
2 11.9 0.040 0.040 0.130 0.000 0.000
3 11.9 0.040 0.040 0.130 0.000 0.000
4 11.6 0.040 0.040 0.130 0.000 0.000
5 Branch -- -- -- -- --
6 -trib- -- -- -- -- --
7 11.6 0.040 0.040 0.130 0.000 0.000
8 11.6 0.040 0.040 0.130 0.000 0.000
9 -trib- -- -- -- -- --
10 11.6 0.040 0.040 0.130 0.000 0.000
11 11.7 0.040 0.040 0.130 0.000 0.000
12 11.7 0.040 0.040 0.130 0.000 0.000
13 12.7 0.040 0.040 0.130 0.000 0.000
14 12.7 0.040 0.040 0.130 0.000 0.000
15 12.7 0.040 0.040 0.130 0.000 0.000
16 -trib- -- -- -- -- --
17 12.7 0.040 0.040 0.130 0.000 0.000
18 12.7 0.040 0.040 0.130 0.000 0.000
19 -trib- -- -- -- -- --
20 12.7 0.040 0.040 0.130 0.000 0.000
21 -trib- -- -- -- -- --
22 12.7 0.040 0.040 0.130 0.000 0.000
23 12.7 0.040 0.040 0.130 0.000 0.000
24 Branch -- -- -- -- --
25 12.7 0.040 0.040 0.130 0.000 0.000
26 Branch -- -- -- -- --
27 12.7 0.040 0.040 0.130 0.000 0.000

```

```

-(br 2) BRANCH: J Stem
28 11.6 0.040 0.040 0.130 0.000 0.000

```

```

-(br 3) BRANCH: N Stem

```

29 11.9 0.040 0.040 0.130 0.000 0.000

-(br 4) BRANCH: O Stem

30 13.0 0.040 0.040 0.130 0.000 0.000

31 12.9 0.040 0.040 0.130 0.000 0.000

=====

SF = 0.0 1.00 1.00 1.00 1.00 1.00

Current Variable Status --> OFF OFF

CAUTION: Kd for CBOD should NEVER exceed Kr for CBOD.

NOTE: Nitrification Inhibition switch now turned OFF, thus

Kd,NBOD rates are NOT inhibited in the Calculations.

Model File Name: LR31204

Calibration of Little River Model

Data from 3-12-2004

4-21-04

Before SOD and CBODk measured data

\*\*\* RATES: REAER, SOD, P/R (Base e @ 20 Deg.C) \*\*\*

11-21-2004

9:02 pm

=====

RCH BOTTOM SOD nP/R <----- REAERATION PARAMETERS ----->

# fract gsmd mgld fixed ESC dE/TOT Depth Opt -used

=====

-(br 1) MAIN STEM: MainStem

1 1.00 6.00 1.5 0.000 0.114 51.18 -on- O 4.444

2 1.00 6.00 1.5 0.000 0.114 56.75 -on- O 4.444

3 1.00 6.00 1.5 0.000 0.114 52.75 -on- O 4.444

4 1.00 6.00 1.5 0.000 0.114 67.36 -on- O 10.471

5 Branch -- - -- -- --

6 -trib- -- - -- -- --

7 1.00 6.00 1.5 0.000 0.114 43.01 -on- O 10.471

8 1.00 6.00 1.5 0.000 0.114 0.00 -on- O 10.471

9 -trib- -- - -- -- --

10 1.00 6.00 1.5 0.000 0.114 43.67 -on- O 10.471

11 1.00 6.00 1.5 0.000 0.114 7.47 -on- O 5.392

12 1.00 6.00 1.5 0.000 0.114 0.00 -on- O 5.392

13 1.00 6.00 1.5 0.000 0.114 5.14 -on- O 1.775

14 1.00 6.00 1.5 0.000 0.114 0.00 -on- O 1.775

15 1.00 6.00 1.5 0.000 0.114 3.26 -on- O 1.775

16 -trib- -- - -- -- --

17 1.00 6.00 1.5 0.000 0.114 6.26 -on- O 1.775

```

18 1.00 6.00 1.5 0.000 0.114 8.06 -on- O 1.775
19 -trib- -- - -- -- -- ---
20 1.00 6.00 1.5 0.000 0.114 0.00 -on- O 1.775
21 -trib- -- - -- -- -- ---
22 1.00 6.00 1.5 0.000 0.114 0.00 -on- O 1.775
23 1.00 6.00 1.5 0.000 0.114 0.00 -on- O 1.775
24 Branch -- - -- -- -- ---
25 1.00 6.00 1.5 0.000 0.114 7.78 -on- O 1.775
26 Branch -- - -- -- -- ---
27 1.00 6.00 1.5 0.000 0.114 0.00 -on- O 1.775

```

```

-(br 2) BRANCH: J Stem
28 1.00 6.00 1.5 0.000 0.114 110.04 -on- O 10.471

```

```

-(br 3) BRANCH: N Stem
29 1.00 6.00 1.5 0.000 0.114 2.94 -on- O 1.600

```

```

-(br 4) BRANCH: O Stem
30 1.00 6.00 1.5 0.000 0.114 20.80 -on- O 1.600
31 1.00 6.00 1.5 0.000 0.114 26.48 -on- O 1.847

```

```

=====
SF = 1.00 1.00 1.00 --- 1.00 -- 1.00
STATUS --> ON ON

```

If PhotoSynthesis > Respiration, then Net P/R is (+).  
NOTE: 'used' - shows the Value actually 'used' in calculations.  
'fixed' - identifies the K2 value fixed-by-user Input.  
I - means K2 'used' is INPUT (I), fixed by user.  
T or O - K2 is CALCULATED, Tsivoglou (T) or O'Connor (O).  
\*T - O'Connor selected, DEPTH disabled, Tsivoglou used.  
Model File Name: LR31204

Calibration of Little River Model  
Data from 3-12-2004  
4-21-04  
Before SOD and CBODk measured data

```

*** REACH WATER QUALITY INPUT DATA ***
11-21-2004 9:02 pm
=====
RCH TEMP CBODu NBODu <---- DO PARAMS ----> *pH TNH3 Sub#2
# degC mg/l mg/l fixed %Sat Opt -used mg/l ---
=====

```

```

-(br 1) MAIN STEM: MainStem
 1 11.9 17.0 1.7 7.60 50.0 | 7.60 6.7 0.00 0.000E+00
 2 11.9 17.0 1.7 7.60 50.0 | 7.60 6.7 0.00 0.000E+00
 3 11.9 17.0 1.7 7.60 50.0 | 7.60 6.7 0.00 0.000E+00
 4 11.6 17.0 1.7 7.51 50.0 | 7.51 6.8 0.00 0.000E+00
 5 Branch -- -- -- -- -- - - -
 6 12.4 17.0 1.7 7.51 50.0 | 7.51 trib 0.00 0.000E+00
 7 11.6 17.0 1.7 7.51 50.0 | 7.51 6.8 0.00 0.000E+00
 8 11.6 17.0 1.7 7.51 50.0 | 7.51 6.8 0.00 0.000E+00
 9 11.7 17.0 1.7 7.51 50.0 | 7.51 trib 0.00 0.000E+00
10 11.6 17.0 1.7 7.51 50.0 | 7.51 6.7 0.00 0.000E+00
11 11.7 17.0 1.7 7.49 50.0 | 7.49 6.7 0.00 0.000E+00
12 11.7 17.0 1.7 7.49 50.0 | 7.49 6.7 0.00 0.000E+00
13 12.7 17.0 1.7 6.60 50.0 | 6.60 6.7 0.00 0.000E+00
14 12.7 17.0 1.7 6.60 50.0 | 6.60 6.7 0.00 0.000E+00
15 12.7 17.0 1.7 6.60 50.0 | 6.60 6.7 0.00 0.000E+00
16 12.7 17.0 1.7 6.60 50.0 | 6.60 trib 0.00 0.000E+00
17 12.7 17.0 1.7 6.60 50.0 | 6.60 6.7 0.00 0.000E+00
18 12.7 17.0 1.7 6.60 50.0 | 6.60 6.7 0.00 0.000E+00
19 12.7 17.0 1.7 6.60 50.0 | 6.60 trib 0.00 0.000E+00
20 12.7 17.0 1.7 6.60 50.0 | 6.60 6.7 0.00 0.000E+00
21 12.7 17.0 1.7 6.60 50.0 | 6.60 trib 0.00 0.000E+00
22 12.7 17.0 1.7 6.60 50.0 | 6.60 6.7 0.00 0.000E+00
23 12.7 17.0 1.7 6.60 50.0 | 6.60 6.7 0.00 0.000E+00
24 Branch -- -- -- -- -- - - -
25 12.7 17.0 1.7 3.00 50.0 | 3.00 6.7 0.00 0.000E+00
26 Branch -- -- -- -- -- - - -
27 12.7 17.0 1.7 6.60 50.0 | 6.60 6.7 0.00 0.000E+00

```

```

-(br 2) BRANCH: J Stem
28 11.6 17.0 1.7 7.03 50.0 | 7.03 6.8 0.00 0.000E+00

```

```

-(br 3) BRANCH: N Stem
29 11.9 17.0 1.7 7.64 50.0 | 7.64 6.8 0.00 0.000E+00

```

```

-(br 4) BRANCH: O Stem
30 13.0 17.0 1.7 8.18 50.0 | 8.18 7.0 0.00 0.000E+00
31 12.9 17.0 1.7 8.18 50.0 | 8.18 7.0 0.00 0.000E+00

```

```

=====

```

```

SF = 0.0 1.00 1.00 -- 1.00 1.00 1.00 1.00 1.00
Current Variable Status --> OFF OFF
*pH is SET-by-user, ONLY used for Ammonia Toxicity calculations.
DO Saturation is based on the STANDARD METHODS equation.
Elevation Correction for DO Saturation has been turned ON.
NOTE: 'used' - shows the Value actually 'used' in calculations.
      'fixed' - identifies the DO value fixed-by-user Input.

```

I or C - reach DO 'used' is INPUT (I), or CALCULATED (C).  
Model File Name: LR31204

Calibration of Little River Model  
Data from 3-12-2004  
4-21-04  
Before SOD and CBODk measured data

\*\*\* FIELD CALIBRATION DATA \*\*\*

11-21-2004 9:02 pm

=====

RCH #	RIVER Mile	CBODu mg/l	NBODu mg/l	DoDEF mg/l	DO ---	TNH3	Sub#2
-------	------------	------------	------------	------------	--------	------	-------

=====

-(br 1) MAIN STEM: MainStem

1	24.53	6.97	0.60	-1.00x	3.29	-1.00x	-1.000E+00x
4	20.09	-1.00x	-1.00x	-1.00x	7.03	-1.00x	-1.000E+00x
7	18.82	16.00	1.43	-1.00x	7.51	-1.00x	-1.000E+00x
13	11.44	14.97	1.32	-1.00x	7.49	-1.00x	-1.000E+00x
27	0.38	14.03	1.15	-1.00x	6.60	-1.00x	-1.000E+00x

-(br 2) BRANCH: J Stem

-(br 3) BRANCH: N Stem

-(br 4) BRANCH: O Stem

=====

Current Variable Status --> OFF OFF

NOTE: Field Data MUST represent 'Head-of-Reach' RiverMiles.

(-1.00x) means 'No Field Data' for that location.

Calibration File Name: LR31204

Model File Name: LR31204

## Appendix E: DoSag Calibration Modeled Results

\* \* \* CALCULATED REACH RESULTS \* \* \*

11-21-2004

9:02 pm

=====

==

RCH #	TYPE	CBODu mg/l	NBODu mg/l	DO mg/l	***DO MIN*** RM	TNH3 mg/l	Sub#2 ---
-------	------	---------------	---------------	------------	--------------------	--------------	--------------

=====

==

-(br 1) MAIN STEM: MainStem

1	stream	6.0	0.5	3.29	3.29	24.53	0.00	0.000E+00
2	stream	14.0	1.3	8.21	7.91	22.04	0.00	0.000E+00
3	stream	15.4	1.5	8.20	8.02	20.90	0.00	0.000E+00
4	stream	15.8	1.5	8.20	8.20	20.09	0.00	0.000E+00
5	Branch	15.7	1.5	9.14	8.98	18.82	0.00	0.000E+00
6	-trib-	15.8	1.4	8.98	8.98	18.82	0.00	0.000E+00
7	stream	15.8	1.4	8.98	8.90	18.82	0.00	0.000E+00
8	stream	15.8	1.4	9.41	9.19	16.84	0.00	0.000E+00
9	-trib-	15.9	1.4	9.38	8.88	15.86	0.00	0.000E+00
10	stream	16.2	1.5	8.88	8.71	15.86	0.00	0.000E+00
11	stream	16.2	1.5	9.40	7.54	12.32	0.00	0.000E+00
12	stream	15.7	1.4	7.54	7.54	12.10	0.00	0.000E+00
13	stream	15.5	1.3	7.54	5.61	9.63	0.00	0.000E+00
14	stream	14.7	1.2	5.61	5.56	8.88	0.00	0.000E+00
15	stream	14.4	1.1	5.56	5.54	7.93	0.00	0.000E+00
16	-trib-	14.1	1.1	5.54	5.54	7.93	0.00	0.000E+00
17	stream	15.0	1.3	5.87	5.60	6.94	0.00	0.000E+00
18	stream	14.6	1.2	5.60	5.55	5.79	0.00	0.000E+00
19	-trib-	14.1	1.1	5.55	5.55	5.79	0.00	0.000E+00
20	stream	14.3	1.1	5.61	5.56	4.05	0.00	0.000E+00
21	-trib-	13.5	1.0	5.56	5.56	3.83	0.00	0.000E+00
22	stream	13.8	1.0	5.66	5.58	2.65	0.00	0.000E+00
23	stream	13.4	1.0	5.58	5.57	1.79	0.00	0.000E+00
24	Branch	13.0	0.9	5.57	5.57	1.57	0.00	0.000E+00
25	stream	13.4	0.9	5.75	5.59	0.38	0.00	0.000E+00
26	Branch	13.0	0.9	5.59	5.59	0.38	0.00	0.000E+00
27	stream	13.2	0.9	5.67	5.63	0.00	0.00	0.000E+00
eBr	----	13.1	0.9	5.63	--	--	0.00	0.000E+00

```

-(br 2) BRANCH: J Stem
28 stream 16.0 1.3 7.03 7.03 19.85 0.00 0.000E+00
eBr ---- 16.0 1.3 8.67 -- -- 0.00 0.000E+00

```

```

-(br 3) BRANCH: N Stem
29 stream 16.0 1.3 7.64 7.00 1.57 0.00 0.000E+00
eBr ---- 15.9 1.3 7.00 -- -- 0.00 0.000E+00

```

```

-(br 4) BRANCH: O Stem
30 stream 18.0 1.3 9.13 6.57 1.69 0.00 0.000E+00
31 stream 16.6 1.4 6.57 6.57 1.69 0.00 0.000E+00
eBr ---- 16.3 1.4 6.63 -- -- 0.00 0.000E+00

```

```

=====
==

```

```

Current Variable Status -->          OFF   OFF
All Results (except DO Min) represent the 'Head-of-Reach'.
DO Saturation is based on the STANDARD METHODS equation.
Elevation Correction for DO Saturation has been turned ON.
Model File Name: LR31204

```

Calibration of Little River Model  
Data from 3-12-2004  
4-21-04  
Before SOD and CBODk measured data

```

*** PROCESSED REACH DATA ***
11-21-2004          9:02 pm

```

```

=====
RCH RIVER WIDTH CUM  VEL TOT  K2@T TEMP rDO
# Mile ft  Flow  fps days /day degC mg/l
=====

```

```

-(br 1) MAIN STEM: MainStem
1 24.53  5.6   0.53 0.20 0.762  3.668 11.9  7.60
2 22.04 13.6   2.13 0.20 0.347  3.668 11.9  7.60
3 20.90 22.3   4.32 0.20 0.249  3.668 11.9  7.60
4 20.09 12.8   6.31 0.53 0.146  8.588 11.6  7.51
5 Branch -   6.31 -- -- -- -- --
6 -trib- -   9.77 -- -- -- 12.4 7.51
7 18.82 20.4   9.77 0.53 0.229  8.588 11.6  7.51
8 16.84 22.4  10.35 0.53 0.112  8.588 11.6  7.51
9 -trib- -  11.74 -- -- -- 11.7 7.51
10 15.86 35.1  16.05 0.53 0.225  8.580 11.6  7.51

```

11	13.91	352.2	18.59	0.07	1.317	4.429	11.7	7.49
12	12.32	382.2	20.35	0.07	0.730	4.429	11.7	7.49
13	11.44	265.1	21.90	0.06	1.913	1.493	12.7	6.60
14	9.63	273.0	22.46	0.06	0.799	1.493	12.7	6.60
15	8.88	280.4	23.23	0.06	1.007	1.493	12.7	6.60
16	-trib-	-	23.68	--	--	--	12.7	6.60
17	7.93	414.7	34.47	0.06	1.047	1.493	12.7	6.60
18	6.94	419.3	34.92	0.06	1.221	1.493	12.7	6.60
19	-trib-	-	35.24	--	--	--	12.7	6.60
20	5.79	451.7	37.38	0.06	2.070	1.493	12.7	6.60
21	-trib-	-	38.20	--	--	--	12.7	6.60
22	3.83	511.0	42.28	0.06	1.256	1.493	12.7	6.60
23	2.65	518.9	43.23	0.06	1.139	1.493	12.7	6.60
24	Branch	-	43.61	--	--	--	--	--
25	1.57	612.9	50.96	0.06	1.265	1.493	12.7	3.00
26	Branch	-	51.60	--	--	--	--	--
27	0.38	664.6	55.50	0.06	0.400	1.493	12.7	6.60
eBr	0.00	-	55.70	--	16.233	--	--	--

-(br 2) BRANCH: J Stem

28	19.85	6.8	3.24	0.53	0.119	8.588	11.6	7.03
eBr	18.82	-	3.46	--	0.119	--	--	--

-(br 3) BRANCH: N Stem

29	3.28	31.5	4.73	0.10	1.020	1.320	11.9	7.64
eBr	1.57	-	7.36	--	1.020	--	--	--

-(br 4) BRANCH: O Stem

30	4.07	11.0	0.88	0.10	1.420	1.355	13.0	8.18
31	1.69	19.3	3.34	0.11	0.744	1.559	12.9	8.18
eBr	0.38	-	3.90	--	2.163	--	--	--

=====

SF = -- --- -- 1.00 --- 1.00 0.0 1.00

(?) - means Width cannot be calculated (Depth turned OFF).

Cumulative FLOW represents the inflow to 'Head-of-Reach'.

rDO is the DO concentration of Reach Incremental Flows.

Model File Name: LR31204

Validation of Little River Model

Data from 3-12-2004

4-21-04

Before SOD and CBODk measured data

\*\*\* RATES: BOD, TNH3, Sub#2 (Base e @ T Deg.C) \*\*\*  
 11-21-2004 9:02 pm

=====

RCH	TEMP	Kr,CBOD	Kd,CBOD	INHIB	Kd,NBOD	K,TNH3	K,Sub#2
#	degC	/day	/day	Factor	/day	/day	/day

=====

-(br 1) MAIN STEM: MainStem

1	11.9	0.028	0.028	1.000	0.070	0.000	0.000
2	11.9	0.028	0.028	1.000	0.070	0.000	0.000
3	11.9	0.028	0.028	1.000	0.070	0.000	0.000
4	11.6	0.027	0.027	1.000	0.068	0.000	0.000
5	Branch	--	--	--	--	--	--
6	-trib-	--	--	--	--	--	--
7	11.6	0.027	0.027	1.000	0.068	0.000	0.000
8	11.6	0.027	0.027	1.000	0.068	0.000	0.000
9	-trib-	--	--	--	--	--	--
10	11.6	0.027	0.027	1.000	0.068	0.000	0.000
11	11.7	0.027	0.027	1.000	0.069	0.000	0.000
12	11.7	0.027	0.027	1.000	0.069	0.000	0.000
13	12.7	0.029	0.029	1.000	0.074	0.000	0.000
14	12.7	0.029	0.029	1.000	0.074	0.000	0.000
15	12.7	0.029	0.029	1.000	0.074	0.000	0.000
16	-trib-	--	--	--	--	--	--
17	12.7	0.029	0.029	1.000	0.074	0.000	0.000
18	12.7	0.029	0.029	1.000	0.074	0.000	0.000
19	-trib-	--	--	--	--	--	--
20	12.7	0.029	0.029	1.000	0.074	0.000	0.000
21	-trib-	--	--	--	--	--	--
22	12.7	0.029	0.029	1.000	0.074	0.000	0.000
23	12.7	0.029	0.029	1.000	0.074	0.000	0.000
24	Branch	--	--	--	--	--	--
25	12.7	0.029	0.029	1.000	0.074	0.000	0.000
26	Branch	--	--	--	--	--	--
27	12.7	0.029	0.029	1.000	0.074	0.000	0.000

-(br 2) BRANCH: J Stem

28	11.6	0.027	0.027	1.000	0.068	0.000	0.000
----	------	-------	-------	-------	-------	-------	-------

-(br 3) BRANCH: N Stem

29	11.9	0.028	0.028	1.000	0.070	0.000	0.000
----	------	-------	-------	-------	-------	-------	-------

-(br 4) BRANCH: O Stem

30	13.0	0.029	0.029	1.000	0.076	0.000	0.000
31	12.9	0.029	0.029	1.000	0.075	0.000	0.000

=====

SF = 0.0 1.00 1.00 --- 1.00 1.00 1.00  
 Current Variable Status --> OFF OFF  
 CAUTION: Kd for CBOD should NEVER exceed Kr for CBOD.  
 NOTE: Nitrification Inhibition switch now turned OFF, thus  
 Kd,NBOD rates are NOT inhibited in the Calculations.  
 Model File Name: LR31204

Validation of Little River Model  
 Data from 3-12-2004  
 4-21-04  
 Before SOD and CBODk measured data

\*\*\* RATES: REAER, SOD, P/R (Base e @ T Deg.C) \*\*\*  
 11-21-2004 9:02 pm

```
=====
RCH TEMP nP/R BOTTOM SOD DEPTH rSOD K2,REAERATION
# degC mgld fract gsmd m mg/l Opt /day
=====
```

```
-(br 1) MAIN STEM: MainStem
1 11.9 1.50 1.00 3.60 0.36 9.94 O 3.668
2 11.9 1.50 1.00 3.60 0.36 9.94 O 3.668
3 11.9 1.50 1.00 3.60 0.36 9.94 O 3.668
4 11.6 1.50 1.00 3.54 0.28 12.50 O 8.588
5 Branch -- -- -- -- --
6 -trib- -- -- -- -- --
7 11.6 1.50 1.00 3.54 0.28 12.50 O 8.588
8 11.6 1.50 1.00 3.54 0.28 12.50 O 8.588
9 -trib- -- -- -- -- --
10 11.6 1.50 1.00 3.54 0.28 12.47 O 8.580
11 11.7 1.50 1.00 3.56 0.23 15.57 O 4.429
12 11.7 1.50 1.00 3.56 0.23 15.57 O 4.429
13 12.7 1.50 1.00 3.79 0.44 8.57 O 1.493
14 12.7 1.50 1.00 3.79 0.44 8.57 O 1.493
15 12.7 1.50 1.00 3.79 0.44 8.57 O 1.493
16 -trib- -- -- -- -- --
17 12.7 1.50 1.00 3.79 0.44 8.57 O 1.493
18 12.7 1.50 1.00 3.79 0.44 8.57 O 1.493
19 -trib- -- -- -- -- --
20 12.7 1.50 1.00 3.79 0.44 8.57 O 1.493
21 -trib- -- -- -- -- --
22 12.7 1.50 1.00 3.79 0.44 8.57 O 1.493
23 12.7 1.50 1.00 3.79 0.44 8.57 O 1.493
```

24	Branch	--	--	--	--	--	--		
25	12.7	1.50	1.00	3.79	0.44	8.57	O	1.493	
26	Branch	--	--	--	--	--	--		
27	12.7	1.50	1.00	3.79	0.44	8.57	O	1.493	

-(br 2) BRANCH: J Stem

28	11.6	1.50	1.00	3.54	0.28	12.50	O	8.588	
----	------	------	------	------	------	-------	---	-------	--

-(br 3) BRANCH: N Stem

29	11.9	1.50	1.00	3.60	0.57	6.28	O	1.320	
----	------	------	------	------	------	------	---	-------	--

-(br 4) BRANCH: O Stem

30	13.0	1.50	1.00	3.86	0.57	6.74	O	1.355	
----	------	------	------	------	------	------	---	-------	--

31	12.9	1.50	1.00	3.83	0.53	7.21	O	1.559	
----	------	------	------	------	------	------	---	-------	--

=====

SF = 0.0 1.00 1.00 1.00 --- --- 1.00

STATUS --> ON ON ON

If PhotoSynthesis > Respiration, then Net P/R is (+).

rSOD = 'Reach SOD', the value actually used in DOsag calcs.

NOTE: I - means Reaeration is INPUT (I), fixed-by-user.

T or O - K2 is CALCULATED, Tsivoglou (T) or O'Connor (O).

\*T - O'Connor chosen, Depth disabled, Tsivoglou used.

Model File Name: LR31204

### Calibration of Little River Model

Data from 3-12-2004

4-21-04

Before SOD and CBODk measured data

### \*\*\* BOD CALIBRATION SUMMARY \*\*\*

11-21-2004 9:02 pm

=====

RCH RIVER <---- CBODu, mg/l ----> <---- NBODu, mg/l ---->

# Mile Calc. - Field = Diff Calc. - Field = Diff

=====

-(br 1) MAIN STEM: MainStem

1	24.5	6.00	6.97	-0.97	0.50	0.60	-0.10	
---	------	------	------	-------	------	------	-------	--

2	22.0	13.96	--	--	1.33	--	--	
---	------	-------	----	----	------	----	----	--

3	20.9	15.35	--	--	1.48	--	--	
---	------	-------	----	----	------	----	----	--

4	20.1	15.76	--	--	1.52	--	--	
---	------	-------	----	----	------	----	----	--

5	Branch	15.70	--	--	1.51	--	--	
---	--------	-------	----	----	------	----	----	--

6	-trib-	15.81	--	--	1.42	--	--	
---	--------	-------	----	----	------	----	----	--

7	18.8	15.81	16.00	-0.19	1.42	1.43	-0.01
8	16.8	15.78	--	--	1.42	--	--
9	-trib-	15.88	--	--	1.44	--	--
10	15.9	16.18	--	--	1.51	--	--
11	13.9	16.19	--	--	1.51	--	--
12	12.3	15.69	--	--	1.40	--	--
13	11.4	15.47	14.97	0.50	1.35	1.32	0.03
14	9.6	14.68	--	--	1.18	--	--
15	8.9	14.42	--	--	1.13	--	--
16	-trib-	14.06	--	--	1.06	--	--
17	7.9	14.98	--	--	1.26	--	--
18	6.9	14.56	--	--	1.17	--	--
19	-trib-	14.09	--	--	1.07	--	--
20	5.8	14.25	--	--	1.11	--	--
21	-trib-	13.49	--	--	0.96	--	--
22	3.8	13.83	--	--	1.03	--	--
23	2.6	13.41	--	--	0.95	--	--
24	Branch	13.01	--	--	0.88	--	--
25	1.6	13.43	--	--	0.94	--	--
26	Branch	12.99	--	--	0.87	--	--
27	0.4	13.22	14.03	-0.81	0.90	1.15	-0.25
eBr	0.0	13.08	--	--	0.88	--	--

-(br 2) BRANCH: J Stem

28	19.9	16.00	--	--	1.25	--	--
eBr	18.8	16.01	--	--	1.27	--	--

-(br 3) BRANCH: N Stem

29	3.3	16.00	--	--	1.25	--	--
eBr	1.6	15.90	--	--	1.31	--	--

-(br 4) BRANCH: O Stem

30	4.1	18.00	--	--	1.25	--	--
31	1.7	16.57	--	--	1.42	--	--
eBr	0.4	16.28	--	--	1.38	--	--

=====

NOTE: RiverMiles are 'Head-of-Reach' values, thus 'Field'  
data MUST correspond to Head-of-Reach RiverMiles.

Calibration File Name: LR31204

Model File Name: LR31204

Validation of Little River Model  
Data from 3-12-2004

4-21-04  
 Before SOD and CBODk measured data

\*\*\* TNH3, Sub#2 CALIBRATION SUMMARY \*\*\*

11-21-2004 9:02 pm

=====

=  
 RCH RIVER <---TNH3 , mg/l --> <----- Sub#2, --- ----->  
 # Mile Calc - Field = Diff Calc. - Field = Diff

=====

=

-(br 1) MAIN STEM: MainStem

1	24.5	0.00	--	--	0.000E+00	--	--
2	22.0	0.00	--	--	0.000E+00	--	--
3	20.9	0.00	--	--	0.000E+00	--	--
4	20.1	0.00	--	--	0.000E+00	--	--
5	Branch	0.00	--	--	0.000E+00	--	--
6	-trib-	0.00	--	--	0.000E+00	--	--
7	18.8	0.00	--	--	0.000E+00	--	--
8	16.8	0.00	--	--	0.000E+00	--	--
9	-trib-	0.00	--	--	0.000E+00	--	--
10	15.9	0.00	--	--	0.000E+00	--	--
11	13.9	0.00	--	--	0.000E+00	--	--
12	12.3	0.00	--	--	0.000E+00	--	--
13	11.4	0.00	--	--	0.000E+00	--	--
14	9.6	0.00	--	--	0.000E+00	--	--
15	8.9	0.00	--	--	0.000E+00	--	--
16	-trib-	0.00	--	--	0.000E+00	--	--
17	7.9	0.00	--	--	0.000E+00	--	--
18	6.9	0.00	--	--	0.000E+00	--	--
19	-trib-	0.00	--	--	0.000E+00	--	--
20	5.8	0.00	--	--	0.000E+00	--	--
21	-trib-	0.00	--	--	0.000E+00	--	--
22	3.8	0.00	--	--	0.000E+00	--	--
23	2.6	0.00	--	--	0.000E+00	--	--
24	Branch	0.00	--	--	0.000E+00	--	--
25	1.6	0.00	--	--	0.000E+00	--	--
26	Branch	0.00	--	--	0.000E+00	--	--
27	0.4	0.00	--	--	0.000E+00	--	--
eBr	0.0	0.00	--	--	0.000E+00	--	--

-(br 2) BRANCH: J Stem

28	19.9	0.00	--	--	0.000E+00	--	--
eBr	18.8	0.00	--	--	0.000E+00	--	--

```

-(br 3) BRANCH: N Stem
29  3.3  0.00  --  --  0.000E+00  --  --
eBr  1.6  0.00  --  --  0.000E+00  --  --

```

```

-(br 4) BRANCH: O Stem
30  4.1  0.00  --  --  0.000E+00  --  --
31  1.7  0.00  --  --  0.000E+00  --  --
eBr  0.4  0.00  --  --  0.000E+00  --  --

```

```

=====
=

```

```

Status -->  OFF          OFF
NOTE: RiverMiles are 'Head-of-Reach' values, thus 'Field'
      data MUST correspond to Head-of-Reach RiverMiles.
Calibration File Name: LR31204
Model File Name: LR31204

```

Validation of Little River Model  
Data from 3-12-2004  
4-21-04  
Before SOD and CBODk measured data

\*\*\* DO RESULTS & CALIBRATION SUMMARY \*\*\*

11-21-2004 9:02 pm

```

=====
RCH RIVER DoSat %SAT DoSTD <--- DO, mg/l ----> DoDEF
#  Mile River River mg/l Calc - Field = Diff mg/l
=====

```

```

-(br 1) MAIN STEM: MainStem
 1  24.5  10.66  30.9  5.00  3.29  3.29  0.00  7.37
 2  22.0  10.75  76.4  5.00  8.21  --  --  2.54
 3  20.9  10.76  76.2  5.00  8.20  --  --  2.56
 4  20.1  10.77  76.1  5.00  8.20  7.03  1.17  2.57
 5  Branch 10.84  84.4  5.00  9.14  --  --  1.69
 6  -trib- 10.84  82.8  5.00  8.98  --  --  1.86
 7  18.8  10.84  82.8  5.00  8.98  7.51  1.47  1.86
 8  16.8  10.84  86.8  5.00  9.41  --  --  1.43
 9  -trib- 10.84  86.5  5.00  9.38  --  --  1.46
10  15.9  10.84  81.9  5.00  8.88  --  --  1.96
11  13.9  10.85  86.6  5.00  9.40  --  --  1.46
12  12.3  10.83  69.6  5.00  7.54  --  --  3.29
13  11.4  10.83  69.6  5.00  7.54  7.49  0.05  3.29
14  9.6  10.59  53.0  5.00  5.61  --  --  4.98

```

15	8.9	10.60	52.5	5.00	5.56	--	--	5.04
16	-trib-	10.60	52.3	5.00	5.54	--	--	5.05
17	7.9	10.60	55.4	5.00	5.87	--	--	4.72
18	6.9	10.60	52.8	5.00	5.60	--	--	5.00
19	-trib-	10.60	52.3	5.00	5.55	--	--	5.05
20	5.8	10.60	52.9	5.00	5.61	--	--	4.99
21	-trib-	10.60	52.4	5.00	5.56	--	--	5.05
22	3.8	10.60	53.4	5.00	5.66	--	--	4.95
23	2.6	10.60	52.6	5.00	5.58	--	--	5.03
24	Branch	10.60	52.5	5.00	5.57	--	--	5.03
25	1.6	10.60	54.2	5.00	5.75	--	--	4.85
26	Branch	10.61	52.7	5.00	5.59	--	--	5.01
27	0.4	10.61	53.5	5.00	5.67	6.60	-0.93	4.94
eBr	0.0	10.61	53.1	--	5.63	--	--	4.98

-(br 2) BRANCH: J Stem  
 28 19.9 10.65 66.0 5.00 7.03 -- -- 3.62  
 eBr 18.8 10.84 80.0 -- 8.67 -- -- 2.16

-(br 3) BRANCH: N Stem  
 29 3.3 10.80 70.7 5.00 7.64 -- -- 3.16  
 eBr 1.6 10.80 64.8 -- 7.00 -- -- 3.80

-(br 4) BRANCH: O Stem  
 30 4.1 9.85 92.7 5.00 9.13 -- -- 0.72  
 31 1.7 10.52 62.4 5.00 6.57 -- -- 3.96  
 eBr 0.4 10.57 62.7 -- 6.63 -- -- 3.94

=====

NOTE: RiverMiles are 'Head-of-Reach' values, thus 'Field'  
 data MUST correspond to Head-of-Reach RiverMiles.  
 DO Saturation is based on the STANDARD METHODS equation.  
 Elevation Correction for DO Saturation has been turned ON.  
 The DO Standard is a FIXED Minimum value.  
 Calibration File Name: LR31204  
 Model File Name: LR31204

Validation of Little River Model  
 Data from 3-12-2004  
 4-21-04  
 Before SOD and CBODk measured data

\* \* \* PAIRED-RUN PARTITIONS \* \* \*

11-21-2004

9:02 pm

```

=====
RCH VEL K2@T CBODu NBODu DO DoMin TNH3 Sub#2
# fps /day mg/l mg/l mg/l mg/l mg/l ---
=====

```

-(br 1) MAIN STEM: MainStem

```

1 0.20 3.668 6.0 0.5 3.29 3.29 0.00 0.000E+00
2 0.20 3.668 14.0 1.3 8.21 7.91 0.00 0.000E+00
3 0.20 3.668 15.4 1.5 8.20 8.02 0.00 0.000E+00
4 0.53 8.588 15.8 1.5 8.20 8.20 0.00 0.000E+00
5 Branch -- 15.7 1.5 9.14 8.98 0.00 0.000E+00
6 -trib- -- 15.8 1.4 8.98 8.98 0.00 0.000E+00
7 0.53 8.588 15.8 1.4 8.98 8.90 0.00 0.000E+00
8 0.53 8.588 15.8 1.4 9.41 9.19 0.00 0.000E+00
9 -trib- -- 15.9 1.4 9.38 8.88 0.00 0.000E+00
10 0.53 8.580 16.2 1.5 8.88 8.71 0.00 0.000E+00
11 0.07 4.429 16.2 1.5 9.40 7.54 0.00 0.000E+00
12 0.07 4.429 15.7 1.4 7.54 7.54 0.00 0.000E+00
13 0.06 1.493 15.5 1.3 7.54 5.61 0.00 0.000E+00
14 0.06 1.493 14.7 1.2 5.61 5.56 0.00 0.000E+00
15 0.06 1.493 14.4 1.1 5.56 5.54 0.00 0.000E+00
16 -trib- -- 14.1 1.1 5.54 5.54 0.00 0.000E+00
17 0.06 1.493 15.0 1.3 5.87 5.60 0.00 0.000E+00
18 0.06 1.493 14.6 1.2 5.60 5.55 0.00 0.000E+00
19 -trib- -- 14.1 1.1 5.55 5.55 0.00 0.000E+00
20 0.06 1.493 14.3 1.1 5.61 5.56 0.00 0.000E+00
21 -trib- -- 13.5 1.0 5.56 5.56 0.00 0.000E+00
22 0.06 1.493 13.8 1.0 5.66 5.58 0.00 0.000E+00
23 0.06 1.493 13.4 1.0 5.58 5.57 0.00 0.000E+00
24 Branch -- 13.0 0.9 5.57 5.57 0.00 0.000E+00
25 0.06 1.493 13.4 0.9 5.75 5.59 0.00 0.000E+00
26 Branch -- 13.0 0.9 5.59 5.59 0.00 0.000E+00
27 0.06 1.493 13.2 0.9 5.67 5.63 0.00 0.000E+00
eBr -- -- 13.1 0.9 5.63 -- 0.00 0.000E+00

```

-(br 2) BRANCH: J Stem

```

28 0.53 8.588 16.0 1.3 7.03 7.03 0.00 0.000E+00
eBr -- -- 16.0 1.3 8.67 -- 0.00 0.000E+00

```

-(br 3) BRANCH: N Stem

```

29 0.10 1.320 16.0 1.3 7.64 7.00 0.00 0.000E+00
eBr -- -- 15.9 1.3 7.00 -- 0.00 0.000E+00

```

-(br 4) BRANCH: O Stem

```

30 0.10 1.355 18.0 1.3 9.13 6.57 0.00 0.000E+00
31 0.11 1.559 16.6 1.4 6.57 6.57 0.00 0.000E+00

```

eBr -- -- 16.3 1.4 6.63 -- 0.00 0.000E+00

=====

SF = 1.00 1.00

PARTITIONS: the Difference between two successive 'RUNS'.  
(I.E., the current RUN minus the previous RUN.)

Model File Name: LR31204

## Appendix F: Station O Long-Term BOD Data

\*\*\* RAW LAB DO DATA, IN STANDARD FORMAT \*\*\*

11-21-2004

9:08 pm

```

=====
DATA MONTH DAY YEAR TIME TEMP DO REAER DOr
No.      24hr degC mg/l (?) mg/l
=====
 1  06  26 2004 1600 -17.1  9.65  -  --
 2  06  28 2004 1500  20.3  8.66  -  --
 3  06  29 2004 1500  19.7  8.08  -  --
 4  06  30 2004 1700  19.7  7.92  -  --
 5  07  01 2004 1500  19.9  7.49  -  --
 6  07  02 2004 1100  19.6  7.39  -  --
 7  07  06 2004 1100 -19.4  6.21  -  --
 8  07  07 2004 1000  20.4  6.01  -  --
 9  07  09 2004 1400  19.8  5.14  -  --
10  07  12 2004 1400  20.5  4.30  -  --
11  07  14 2004 1400  20.1  3.76  -  --
12  07  15 2004 1500 +20.9  3.58  yes  6.81
13  07  20 2004 1100  20.2  6.40  -  --
14  07  23 2004 1400  20.0  6.08  -  --
15  07  28 2004 1500  20.1  5.18  -  --
16  07  30 2004 1100  20.0  4.92  -  --
17  08  03 2004 1100 -19.4  4.43  -  --
18  08  10 2004 1500  19.9  3.60  -  --
19  08  12 2004 1400 +20.9  3.50  -  --
20  08  20 2004 1300  20.4  2.91< yes  9.45
21  08  27 2004 1300 +20.5  8.53  -  --
22  09  02 2004 1700 +22.0  8.27  -  --
23  09  16 2004 1200  19.8  6.39  -  --
24  09  23 2004 1600  19.8  5.84  -  --
25  10  05 2004 1400  20.3  4.96  -  --
26  10  15 2004 1500  20.4  4.57  -  --
27  10  21 2004 1400  19.8  3.89  -  --
28  10  27 2004 1630  19.7  4.17  -  --
=====

```

```

(<) Lab DO Below Minimum Allowed (3.0 mg/l): Total = 1
(+/-) Temp Drift [Std 19.5 to 20.5 degC]: Total = 7
Number of Reaerations during test = 2 <--OK
Test Name: test 2

```