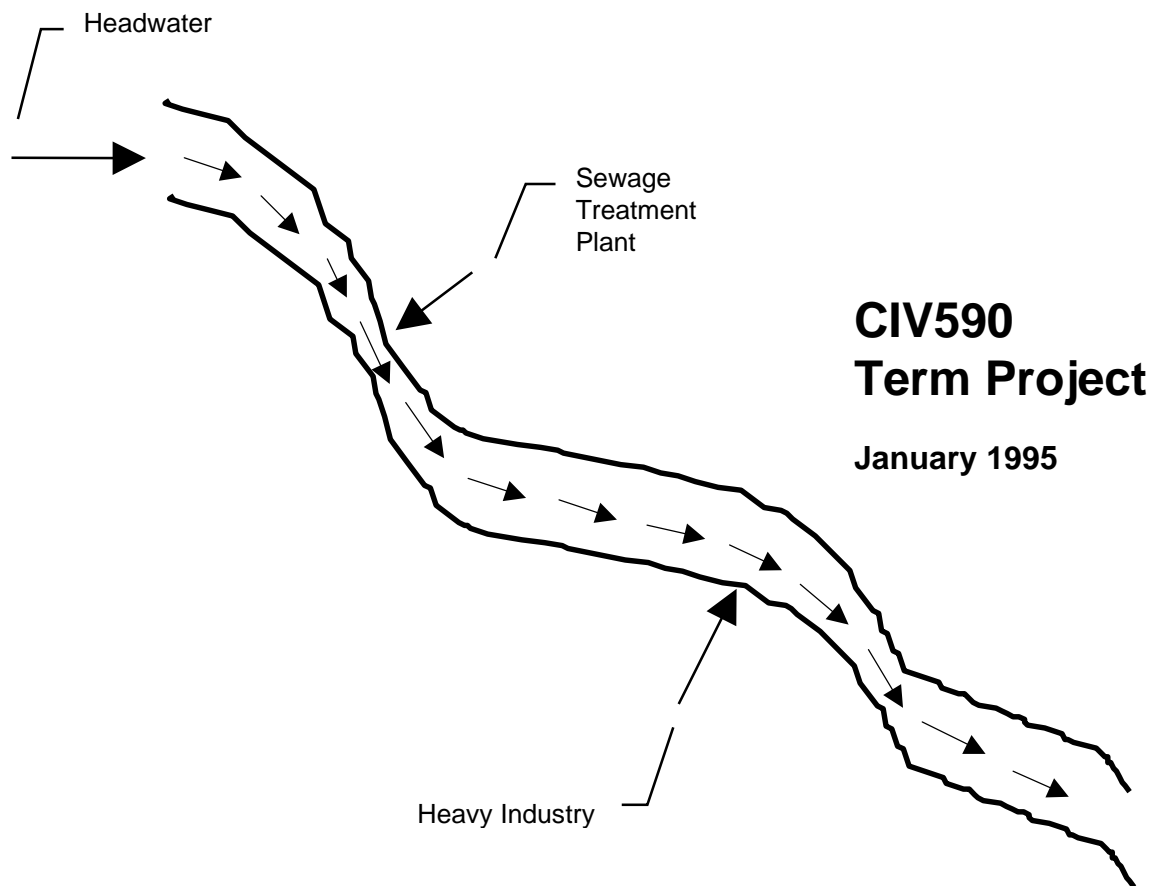


DISSOLVED OXYGEN ANALYSIS OF A STREAM WITH POINT SOURCES



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PREFACE

This report is presented to Princeton University as the Term Project for CIV590, Water Quality Modeling and Analysis, Fall Term, 1994. Please address any questions to:

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1.0 OVERVIEW

1.1 Background

The purpose of this report is twofold: (1) to document the development of the C computer code STREADO (Stream Reach Dissolved Oxygen), and (2) to discuss the phenomena of oxygen utilization in streams with point sources through simulations with STREADO. STREADO was developed to solve the steady-state one-dimensional mass balances of dissolved oxygen and biological oxygen demand (BOD). STREADO analyzes streams with point sources, accounting for the following dissolved oxygen source/sink terms:

- 1) reaeration
- 2) oxidation of carbonaceous BOD (CBOD)
- 3) oxidation of nitrogenous BOD (NBOD)
- 4) photosynthesis
- 5) respiration
- 6) sediment oxygen demand

STREADO solves the following steady-state one-dimensional CBOD, NBOD, and dissolved oxygen mass balance equations for stream flow:

$$0 = -U \frac{\partial L}{\partial x} - K_r L \quad (1)$$

$$0 = -U \frac{\partial L^N}{\partial x} - K_N L^N \quad (2)$$

$$0 = -U \frac{\partial c}{\partial x} - K_d L - K_N L^N + K_a (c_s - c) + p_a - R - S'_B \quad (3)$$

where:

- U = Stream Velocity [L/T]
- x = Distance [L]
- L = CBOD Concentration [M/L³]
- K_r = CBOD Decay Rate [1/T]
- L^N = NBOD Concentration [M/L³]
- K_N = NBOD Decay Rate [1/T]
- c = Dissolved Oxygen Concentration [M/L³]

- K_d = Effective Deoxygenation Rate from CBOD Oxidation [1/T]
 K_a = Volumetric Reaeration Rate [1/T]
 c_s = Saturation Concentration of Dissolved Oxygen [M/L³]
 p_a = Average Gross Photosynthetic Production of Dissolved Oxygen [M/L² T]
 R = Average Respiration Rate [M/L² T]
 S_B' = Sediment Oxygen Demand [M/L² T]

Eqn.'s 1 and 2 state that the change in CBOD and NBOD concentrations along the stream is equal to the first order degradation of those constituents. Eqn. 3 states that the change in dissolved oxygen along the stream is equal to the oxygen utilization for the oxidation of CBOD, NBOD and sediment oxygen demand, production by photosynthesis, utilization by respiration, and reaeration. These equations are discussed in detail in Section 2.

1.2 Method of Solution

STREADO allows the user to divide the stream being examined into various reaches, with each reach having its own defining parameters, such as length, depth, velocity, turbidity, etc. In addition, point sources of dissolved oxygen and BOD can be added at the beginning of a reach. This allows STREADO to solve problems such as:

- Analysis of the effects of dissolved oxygen, CBOD, and NBOD point sources along a stream,
- Addition of tributaries along the stream,
- Changing stream conditions (e.g., depth, velocity, turbidity, available sunlight, etc.).
- Effects of localized high sediment oxygen demand (e.g., sludge buildup at a waste stream outfall).

Initial conditions at the headwater must be specified for the initial reach (CBOD, NBOD, and Dissolved Oxygen Deficit); each additional reach may have an input stream added to the main stream flow at the beginning of the reach. This is illustrated in Figure 1; here we see a two-reach model, with an input stream from a sewage treatment plant injected at the beginning of reach #1.

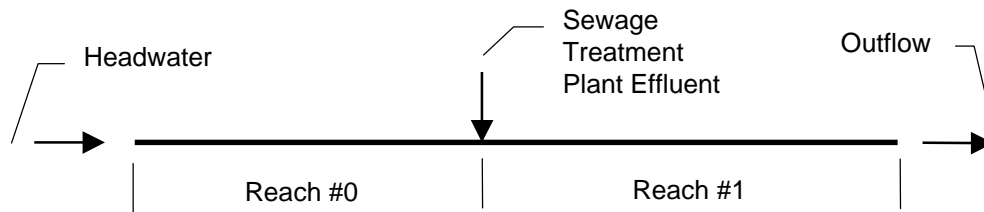


Figure 1. Two-reach model of a stream with a point-source

STREADO analyzes this problem in the following way:

1. STREADO solves Eqn.'s 1 to 3 along Reach #0 based on the initial conditions at the headwater,
2. STREADO mixes the effluent from Reach #0 with the sewage treatment plant effluent.
3. STREADO solves Eqn.'s 1 to 3 along Reach #1 based on the conditions of the mixed flow.

The output from STREADO includes the dissolved oxygen deficit, CBOD, and NBOD concentrations along the stream, along with a comparison to the Streeter-Phelps solution for the same stream conditions (the Streeter-Phelps solution will be discussed in Section 2).

1.3 Assumptions

The following assumptions were made in the formation of the STREADO equations:

1. The main assumption in the formulation of the equations is that the phytoplankton concentration remains constant throughout the stream (i.e., growth - death = settling). The more rigorous analysis of variable phytoplankton concentration requires the addition of nutrient mass balances in the equation formulation. To simplify the analysis, it was assumed that the nutrients were not limiting, and the equations use the average gross production of oxygen from photosynthesis.
2. It is assumed that the temperature is constant throughout the stream. Mixing of different temperature streams is not accounted for.

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2.0 DISCUSSION OF EQUATIONS

This section discusses the parameters of the mass balance equations (Eqn.'s 1 to 3). It should be noted that the equations and terms discussed in this section are taken from Thomann and Mueller's book on surface water quality¹.

2.1 Components

In order to simplify the governing equations, they were rewritten in terms of the dissolved oxygen deficit, D , and the time-of-travel, t^* . First, Eqn. 3 was rewritten in terms of the dissolved oxygen deficit,

$$D = c_s - c \quad (4)$$

where c_s is the saturation value of dissolved oxygen, and is a function of temperature, pressure, and salinity. Substitution of Eqn. 4 into Eqn. 3 gives

$$0 = -U \frac{\partial c_s}{\partial x} + U \frac{\partial D}{\partial x} - K_d L - K_N L^N + K_a D + p_a - R - S'_B \quad (5)$$

Then, assuming that the temperature, pressure, and salinity are constant throughout the stream, we can write

$$U \frac{\partial D}{\partial x} = K_d L + K_d L^N - K_a D - p_a + R + S'_B \quad (6)$$

Next, if we define the time-of-travel as

$$t^* = \frac{x}{U} \quad (7)$$

we can write Eqn.'s 1, 2, and 6 as

¹ R.V. Thomann and J.A. Mueller, "Principles of Surface Water Quality Modeling and Control", Harper Collins Publishers, 1987.

$$\frac{\partial L}{\partial t^*} = -K_r L \quad (8)$$

$$\frac{\partial L^N}{\partial t^*} = -K_N L^N \quad (9)$$

$$\frac{\partial D}{\partial t^*} = K_d L + K_N L^N - K_a D - p_a + R + S'_B \quad (10)$$

It is seen that these are linear, first order differential equations. The terms of Eqn.'s 8 to 10 are discussed in the following sub-sections, and the solutions of these three mass balance equations are presented in Section 2.2.

2.1.1 Reaeration

The rate of change of dissolved oxygen with respect to time to the first approximation can be considered to be proportional to the difference between the saturation concentration of dissolved oxygen (c_s) and the concentration of dissolved oxygen present in the water (c). The saturation concentration of dissolved oxygen in a stream is a function of the partial pressure of oxygen in the atmosphere (via Henry's Law), temperature, and salinity; for this analysis, it was assumed that these properties are constant, and thus, c_s is constant. The mass balance of oxygen via reaeration can be given by

$$\frac{dc}{dt^*} = K_a (c_s - c) \quad (11)$$

or, in terms of the dissolved oxygen deficit,

$$\frac{dD}{dt^*} = -K_a D \quad (12)$$

where c_s is assumed constant.

The term K_a is the volumetric reaeration coefficient, with units $[1/T]$. In natural waters K_a depends on:

1. Internal mixing and turbulence
2. Temperature
3. Wind mixing
4. Waterfalls, dams, and rapids

5. Surface films

Many studies have been performed to determine K_a as a function of internal mixing and turbulence. Once such formulation was based on theoretical considerations regarding surface renewal of the liquid film through internal turbulence, and resulted in (Thomann and Mueller, Eqn. 6.27)

$$K_a = \frac{(D_L U)^{1/2}}{H^{3/2}} = \frac{12.9U^{1/2}}{H^{3/2}} \quad (13)$$

where D_L is the oxygen diffusivity at 20°C, U is the velocity in ft/s, H is the average depth of the stream, and K_a is in day^{-1} . This formulation was verified experimentally on six water bodies ranging in depth from 1 to 30 ft and velocities in the range of 0.5 to 1.6 ft/s. An empirical formulation based on rivers in the Tennessee Valley resulted in (Thomann and Mueller, Eqn. 6.28)

$$K_a = \frac{11.6U}{H^{1.67}} \quad (14)$$

where the units are the same as above. This study examined rivers ranging in depth from 2 to 11 feet and in velocity from 1.8 to 5.0 ft/s. STREADO uses Eqn. 13 for velocities below 1.8 ft/s and Eqn. 14 for velocities above 1.8 ft/s.

The reaeration coefficient as a function of temperature has been given by

$$(K_a)_T = (K_a)_{20} \theta^{T-20} \quad (15)$$

where T is in degrees Celsius and θ depends on the mixing condition of the water body. Values of θ have been given in the range from 1.005 to 1.030, with the value of 1.024 normally used in practice (Thomann and Mueller, pg. 282). STREADO uses a θ of 1.024.

2.1.2 Carbonaceous Biological Oxygen Demand

Carbonaceous biological oxygen demand (CBOD) represents the equivalent oxygen utilization for oxidation of the complex carbonaceous material in a waste stream. The CBOD (L) can be represented as the sum of the particulate CBOD (L_p) and the dissolved CBOD (L_d), where the particulate CBOD can settle out of the water column and become part of the sediment biological oxygen demand. Thus,

$$L = L_p + L_d \quad (16)$$

If we assume that the particulate CBOD settles without oxidation and the dissolved CBOD is oxidized, we can write the mass balances as

$$V \frac{dL_p}{dt^*} = -v_s A L_p \quad (17)$$

$$V \frac{dL_d}{dt^*} = -k'_d V L_d \quad (18)$$

where

- v_s = settling velocity [L/T]
- A = surface area [L²]
- k'_d = CBOD decay rate [1/T]
- V = volume [L³]

If we define the f_d and f_p as the fraction of dissolved and particulate CBOD, respectively, then we can write

$$V \frac{dL}{dt^*} = -v_s A f_p L - K'_d V f_d L = -(K_s + K_d) L = -K_r L \quad (19)$$

where K_s is the effective loss rate due to settling, K_d is the effective deoxygenation rate, and K_r is the overall loss rate [day⁻¹] of CBOD due to both settling and oxidation. It has been found that for effluents with suspended solids of less than 30 mg/L, K_s may be neglected due to the absence of any significant particulate BOD (Thomann and Mueller, pg. 296). The solution to Eqn. 19 gives the CBOD concentration as a function of t^*

$$L = L_0 e^{-K_r t^*} \quad (20)$$

Next, the utilization of oxygen by the oxidation of CBOD can be described by the first order equation

$$\frac{dD}{dt^*} = -K_d L \quad (21)$$

Note that the dissolved oxygen deficit is only a function of the CBOD based on K_d , not K_r , since it is assumed that the particulate CBOD does not oxidize. K_d cannot usually be estimated from bottle tests for streams due to other phenomena which are not simulated in bottle tests, including possible settling of BOD, biosorption by biofilms on the stream bed, stream turbulence and roughness, and density of attached organisms. For these reasons attempts have been made to correlate K_d to stream characteristics. K_d at 20°C has been found to have the relationship (Thomann and Mueller, Eqn. 6.60)

$$K_d = \begin{cases} 0.3 \left(\frac{H}{8} \right)^{-0.434} & 0 \leq H \leq 8 \\ 0.3 & H > 8 \end{cases} \quad (22)$$

where H is the average stream depth in feet and K_d is in day^{-1} . The effect of temperature on K_d may be approximated by

$$(K_d)_T = (K_d)_{20} \theta^{T-20} \quad (23)$$

where the temperature coefficient θ has been reported to vary to 1.02 to 1.09, with the average being 1.047 (Thomann and Mueller, pg. 297). STREADO uses θ of 1.047.

2.1.3 Nitrogenous Biological Oxygen Demand

There are two approaches available for describing the Nitrogenous Biological Oxygen Demand (NBOD). The first approach looks at the kinetic reactions between the organic, ammonia, and nitrite and nitrate nitrogen. The second approach, which is modeled in STREADO, utilizes an overall oxidation rate of the organic and ammonia nitrogen. Assuming first order kinetics, the overall rate of change of the NBOD can be given by

$$\frac{dL^N}{dt^*} = -K_N L^N \quad (24)$$

where K_N [1/T] is the overall oxidation rate of NBOD. The solution to Eqn. 24 is

$$L^N = L_0^N e^{-K_N t^*} \quad (25)$$

Next, the utilization of oxygen by the oxidation of NBOD can be described by the first order equation

$$\frac{dD}{dt^*} = -K_N L^N \quad (26)$$

where the range of K_N values is approximately the same as for the CBOD deoxygenation rate (Thomann and Mueller, pg. 301). Unless input directly by the User, STREADO assumes that $K_N = K_d$. The effect of temperature on K_N may be approximated by

$$(K_N)_T = (K_N)_{20} \theta^{T-20} \quad (27)$$

where the temperature coefficient θ has been reported to vary to 1.0548 to 1.0997, with the average being 1.08 (Thomann and Mueller, pg. 301). STREADO uses θ of 1.08.

2.1.4 Photosynthesis

Aquatic plants and phytoplankton can have a large effect on the dissolved oxygen concentration in a body of water. This effect is due to the photosynthesis process, which uses the sun's energy to convert water and carbon dioxide into glucose. The production of oxygen occurs via the removal of hydrogen from the water, forming a peroxide which breaks down into water and oxygen. This oxygen production via photosynthesis can result in supersaturated dissolved oxygen concentrations, sometimes as high 150 to 200% above the air saturation values (Thomann and Mueller, pg. 284).

There are three methods for determining the average gross production of dissolved oxygen by photosynthesis:

1. "Light and dark" bottle or chamber measurements of dissolved oxygen
2. Estimation from observed chlorophyll α levels
3. Measurement of diurnal DO range

Methods 1 and 3 can be used to estimate the dissolved oxygen production due to phytoplankton and rooted plants. Method 2 estimates the production and respiration for waters where phytoplankton are the principle source of oxygen. This is the method used in STREADO.

If the concentration of chlorophyll α does not change, the relationship between phytoplanktonic chlorophyll and oxygen production depends on temperature, solar radiation, depth, and the light extinction coefficient. It has been shown that if nutrients are not limiting and the chlorophyll α concentration remains constant, then the average gross production of oxygen, p_a [mg DO/L-day] is (Thomann and Mueller, Eqn. 6.40)

$$p_a = [a_{op} G_{max} P] G(I_a) \quad (28)$$

where

- a_{op} = ratio of mg DO/ μ g chl α (range of 0.1 to 0.3)
- G_{max} = maximum growth rate of the phytoplankton (range 1.5 to 3.0/day)
- P = phytoplankton chlorophyll in μ g/L
- $G(I_a)$ = light attenuation factor over depth and one day, given by

$$G(I_a) = \frac{2.718 \cdot f}{K_e H} [e^{-\alpha_1} - e^{-\alpha_0}] \quad (29)$$

$$\alpha_o = \frac{I_a}{I_s} \quad (30)$$

$$\alpha_1 = \alpha_o e^{-K_e z} \quad (31)$$

where K_e = light extinction coefficient [1/m]
 I_a = average solar radiation during the day [langleys/day]
 I_s = light at which phytoplankton grow at max. rate [ly/day] (range 250 - 500)
 f = photoperiod (fractional duration of daylight)

The temperature effect on p_a has been given by

$$(p_a)_T = (p_a)_{20} \theta^{T-20} \quad (32)$$

where $\theta = 1.066$ (Thomann and Mueller, pg. 287). No range was given for θ in the text.

2.1.5 Respiration

Similar to the photosynthesis term, the respiration term is related to the phytoplankton chlorophyll α concentration by (Thomann and Mueller, Eqn. 6.43)

$$R = a_{op} \mu_r P \quad (33)$$

where μ_r is the phytoplankton respiration rate (0.05 to 0.25/day). STREADO uses the value of 0.1 (Thomann and Mueller, Eqn. 6.43). The temperature effect is described by the same equation used for photosynthesis:

$$(R)_T = (R)_{20} \theta^{T-20} \quad (34)$$

where $\theta = 1.08$ (Thomann and Mueller, pg. 290). No range was give for θ in the text.

2.1.6 Sediment Oxygen Demand

Sediment oxygen demand can occur due to the following conditions:

1. Discharge of settleable waste components
2. Growth of filamentous bacteria on soluble organic wastes
3. Death of rooted plants, and leaves and detritus in natural runoff
4. Settling of phytoplankton

The bottom of a stream may vary from deep deposits of sewage or industrial waste to relatively shallow deposits of plant material to clean gravely and sandy bottoms. The oxygen utilization by bottom sediments depends on the organic material present and the nature of the benthic community.

The demand of dissolved oxygen from sediments is a function of the bottom surface area. The total flux can be described by

$$S'_B = \frac{S_B A_B}{V} = \frac{S_B}{H} \quad (35)$$

where

- S'_B = Sediment oxygen demand [mg/L-d]
- S_B = Areal averaged SOD
- A_B = Bottom area
- V = Volume
- H = Average water depth

The temperature effect in the 10 to 30°C range can be described by

$$(S_B)_T = (S_B)_{20} \theta^{T-20} \quad (36)$$

where θ is in the range of 1.040 to 1.130, with the average reported to be 1.065 (Thomann and Mueller, pg. 292). STREADO uses a θ of 1.065.

2.2 Combined Equations

The terms described in the preceding sections are now inserted into Eqn.'s 8, 9, and 10 to formulate the total mass balance equations. The solution to Eqn. 8 was given by Eqn. 20:

$$L = L_0 e^{-K_r t}$$

where K_r is given by

$$K_r = K_s + K_d \quad (37)$$

and K_s is an input to the system and K_d is calculated by Eqn.'s 22 and 23. The solution to Eqn. 9 was given by Eqn. 25:

$$L^N = L_0^N e^{-K_N t}$$

Where K_N is an input to the system with temperature effects defined by Eqn. 26. Substitution of the prior equations into Eqn. 10 and solving gives the following dissolved oxygen deficit equation (Thomann and Mueller, Eqn. 6.106)

$$\begin{aligned}
 D = & D_o e^{-K_a t} \\
 & + \left\{ \frac{K_d}{K_a - K_r} (e^{-K_r t} - e^{-K_a t}) \right\} L_o \\
 & + \left\{ \frac{K_N}{K_a - K_N} (e^{-K_N t} - e^{-K_a t}) \right\} L_o^N \\
 & + \left\{ \frac{1}{K_a} (1 - e^{-K_a t}) \right\} (-p_a + R + S'_B)
 \end{aligned} \tag{38}$$

where the photosynthesis, respiration, and areal SOD terms are given by Eqn.'s 28-36. Given the appropriate initial conditions and coefficients, STREADO calculates for the unknown coefficients and solves the mass balances given by Eqn.'s 20, 22, and 38.

STREADO also outputs the Streeter-Phelps solution for the stream being analyzed. The Streeter-Phelps solution only considers reaeration and CBOD; therefore, to solve the Streeter-Phelps equation, STREADO sets the NBOD, photosynthesis, respiration, and SOD terms to zero and solves Eqn. 38 for the dissolved oxygen deficit. This allows comparison of the full dissolved oxygen deficit results to the simplified Streeter-Phelps results.

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3.0 DESCRIPTION OF CODE

3.1 Procedure

Given “n” reaches, STREADO solves for each reach in turn, starting from reach zero and working sequentially to reach n. The reaches must be numbered sequentially, or STREADO will return an error message. The procedure for solving this problem is given in Figure 2. The source listing of STREADO is included as Appendix A.

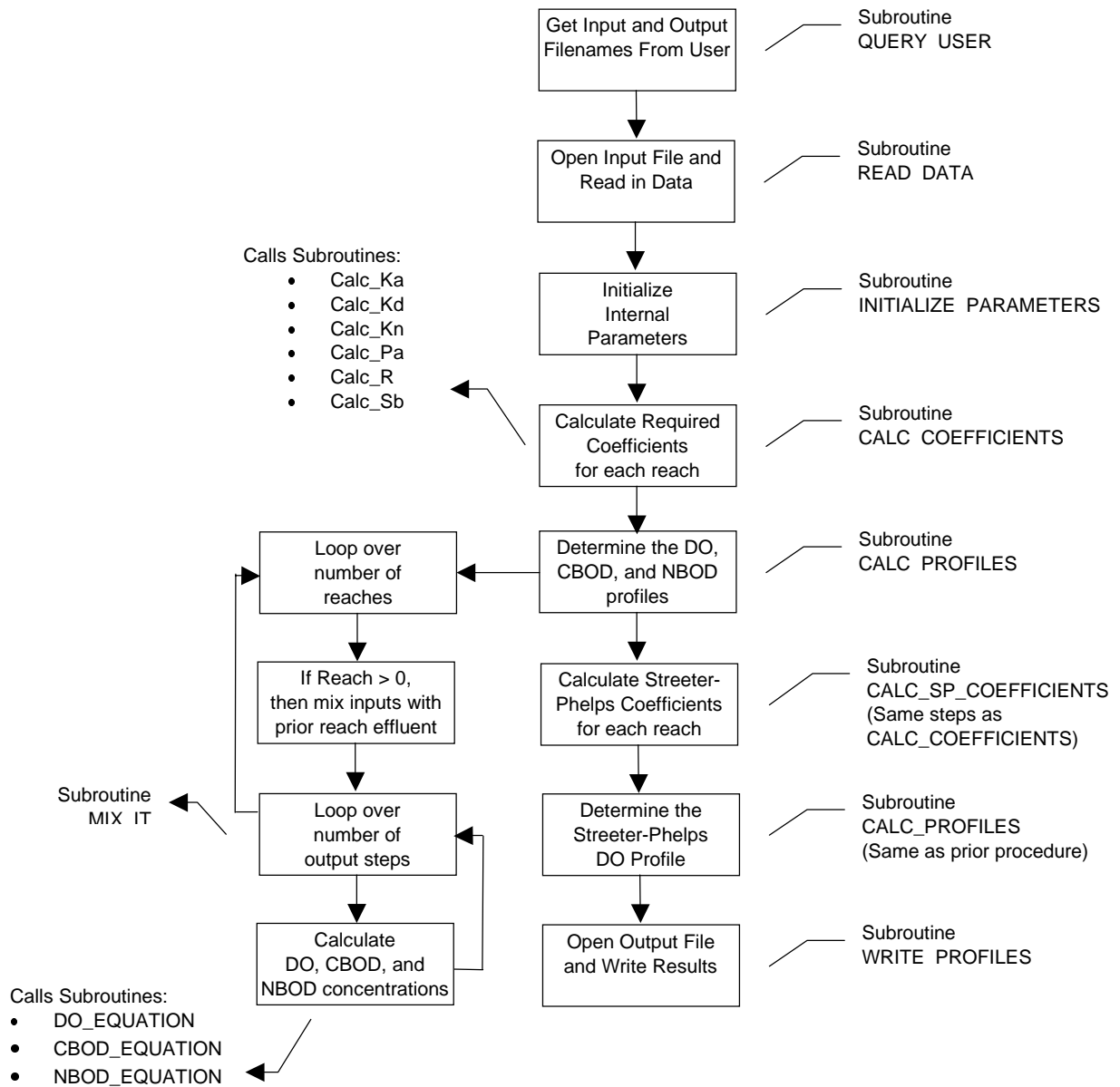


Figure 2. STREADO Flow Diagram

3.2 Description of Subroutines

A brief description of the purpose of each subroutine is given below.

- A. QUERY_USER: Queries user for input and output filenames.
- B. READ_DATA: Reads input data from input file.
- C. INITIALIZE_PARAMETERS: Initializes required parameters.
- D. CALC K_a: Calculates K_a based on Eqn.'s 13 to 15.
- E. CALC K_d: Calculates K_d based on Eqn.'s 22 and 23.
- F. CALC K_n: For now, sets $K_n = K_d$ and adjusts via Eqn. 26.
- G. CALC P_a: Calculates p_a based on Eqn.'s 27 through 31.
- H. CALC R: Calculates R based on Eqn.'s 32 and 33.
- I. CALC S_b: Calculates S_b based on Eqn.'s 34 and 35.
- J. CALC COEFFICIENTS: Calls the above coefficient subroutines, or sets the coefficients equal to user specified values.
- K. DO EQUATION: Solves for the dissolved oxygen deficit from Eqn. 37.
- L. CBOD EQUATION: Solves for the CBOD concentration from Eqn. 20.
- M. NBOD EQUATION: Solves for the NBOD concentration from Eqn. 25.
- N. CALC PROFILE: Loops over the number of reaches and through the number of steps for reach reach to calculate the DO Deficit, CBOD, and NBOD profiles.
- O. MIX_IT: Mixes input streams with prior reach effluent.
- P. CALC SP COEFFICIENTS: Calculates the coefficients for the Streeter-Phelps solution.
- Q. WRITE PROFILES: Outputs the profiles to the output file.

3.3 Input File Format

The input file is broken down into two sections: (1) general inputs and (2) reach specific inputs. The general inputs include the number of reaches and the non-reach-specific data such as phytoplankton rates and water temperature. The reach specific inputs include data on the reach

configuration, influent waste streams or tributaries, and rate constants. The user has the option of inputting the various coefficients directly, or allowing STREADO to calculate them. If the coefficients are set negative in the input file, then STREADO calculates the appropriate values; if they are positive, the the input values are used. An example two reach input file is shown in Figure 3, along with the required units.

3.4 Output File Format

The output is presented in a comma delimited format for inclusion into a spreadsheet for analysis and plotting. The specific information in the output file is:

1. Reach number
2. Distance from start [feet]
3. Distance from start [miles]
4. Dissolved oxygen deficit [mg/L]
5. CBOD concentration [mg/L]
6. NBOD concentration [mg/L]
7. Streeter-Phelps dissolved oxygen deficit [mg/L]

Title: This is an example input file

```

**** Constants ****
3          nreaches          number of reaches
20.0       Temperature      Water temperature [10-30 deg C]
30.0       P                Phytoplankton chlorophyl [5-500 micro-g/L]
300.0      Is               Solar rad. at max phy. growth [250-500 ly/day]
0.50       f                Photoperiod [day]
0.2        aop              DO/chlorophyl alpha ratio [0.1-0.3 (mg DO)/(micro-g chl a)]
1.8        Gmax             Max. phyto. growth rate [1.5-3.0 1/d]

**** REACH 0 ****
1000000.0  Length           Length of reach [ft]
1.0        Velocity         Flow velocity [ft/s]
5.0        Depth            Average stream depth [ft]
1000.0     Flow             Flow rate [ft^3/s]
-1.0      Ka                Reaeration coefficient [1/d]
-1.0      Kd                Effective deoxygenation rate [1/d]
-1.0      Kr                Overall loss rate [1/d]
-1.0      Kn                Nitrification rate [1/d]
-1.0      Pa                Average gross DO prod. [mg DO/(L day)]
-1.0      R                 Respiration rate [mg DO/(L day)]
-1.0      Sb                Sediment oxygen demand [mg DO/(L day)]
0.50      Areal_Sb         Areal averaged SOD rate [0.05-5.0 g DO/(L day)]
1.00      Ke                Light extinction coefficient [0.1-5.0/m]
750.0     Ia                Avg. daily solar rad. [500-1000 ly/day]
250       nsteps           Numer of steps to loop over
0.0       initial DO       Initial DO Deficit [mg/L]
20.0      initial CBOD     Initial CBOD concentration [mg/L]
10.0      initial NBOD     Initial NBOD concentration [mg/L]

**** REACH 1 ****
1000000.0  Length           Length of reach [ft]
1.0        Velocity         Flow velocity [ft/s]
5.0        Depth            Average stream depth [ft]
1000.0     Flow             Flow rate [ft^3/s]
-1.0      Ka                Reaeration coefficient [1/d]
-1.0      Kd                Effective deoxygenation rate [1/d]
-1.0      Kr                Overall loss rate [1/d]
-1.0      Kn                Nitrification rate [1/d]
-1.0      Pa                Average gross DO prod. [mg DO/(L day)]
-1.0      R                 Respiration rate [mg DO/(L day)]
-1.0      Sb                Sediment oxygen demand [mg DO/(L day)]
0.50      Areal_Sb         Areal averaged SOD rate [0.05-5.0 g DO/(L day)]
1.00      Ke                Light extinction coefficient [0.1-5.0/m]
750.0     Ia                Avg. daily solar rad. [500-1000 ly/day]
250       nsteps           Numer of steps to loop over
0.0       initial DO       Initial DO Deficit [mg/L]
50.0      initial CBOD     Initial CBOD concentration [mg/L]
10.0      initial NBOD     Initial NBOD concentration [mg/L]

**** REACH 2 ****
1000000.0  Length           Length of reach [ft]
1.0        Velocity         Flow velocity [ft/s]
5.0        Depth            Average stream depth [ft]
1000.0     Flow             Flow rate [ft^3/s]
-1.0      Ka                Reaeration coefficient [1/d]
-1.0      Kd                Effective deoxygenation rate [1/d]
-1.0      Kr                Overall loss rate [1/d]
-1.0      Kn                Nitrification rate [1/d]
-1.0      Pa                Average gross DO prod. [mg DO/(L day)]
-1.0      R                 Respiration rate [mg DO/(L day)]
-1.0      Sb                Sediment oxygen demand [mg DO/(L day)]
0.50      Areal_Sb         Areal averaged SOD rate [0.05-5.0 g DO/(L day)]
1.00      Ke                Light extinction coefficient [0.1-5.0/m]
750.0     Ia                Avg. daily solar rad. [500-1000 ly/day]
250       nsteps           Numer of steps to loop over
0.0       initial DO       Initial DO Deficit [mg/L]
50.0      initial CBOD     Initial CBOD concentration [mg/L]
10.0      initial NBOD     Initial NBOD concentration [mg/L]

```

Figure 3. Example STREADO Input File With Three Reaches

4.0 ANALYSIS

4.1 Sensitivity Analysis

Sensitivity analyses were performed in order to analyze the importance each parameter has on the dissolved oxygen deficit in a stream. A baseline case was set-up in order to perform the sensitivity analyses. This baseline case is outlined in Figure 4, and the STREADO baseline sensitivity input file is included in Appendix B.

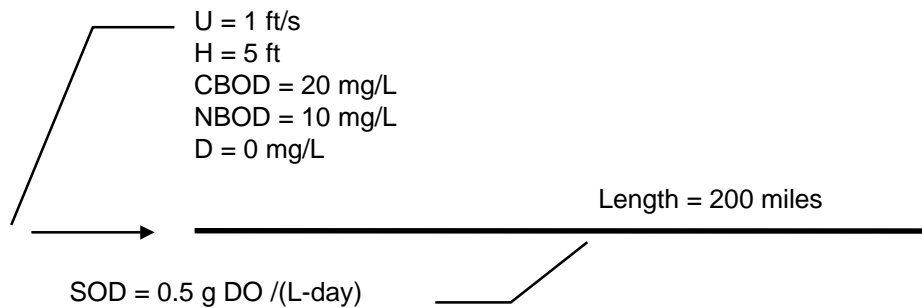


Figure 4 - Sensitivity Analysis Baseline Stream

Sensitivity analyses were performed on the following variables:

- Average Stream Velocity
- Areal Sediment Oxygen Demand
- Biological Oxygen Demand
- Water Temperature
- Phytoplankton Chlorophyll α Concentration
- Light Extinction Coefficient
- Average Daily Solar Radiation
- Average Water Depth

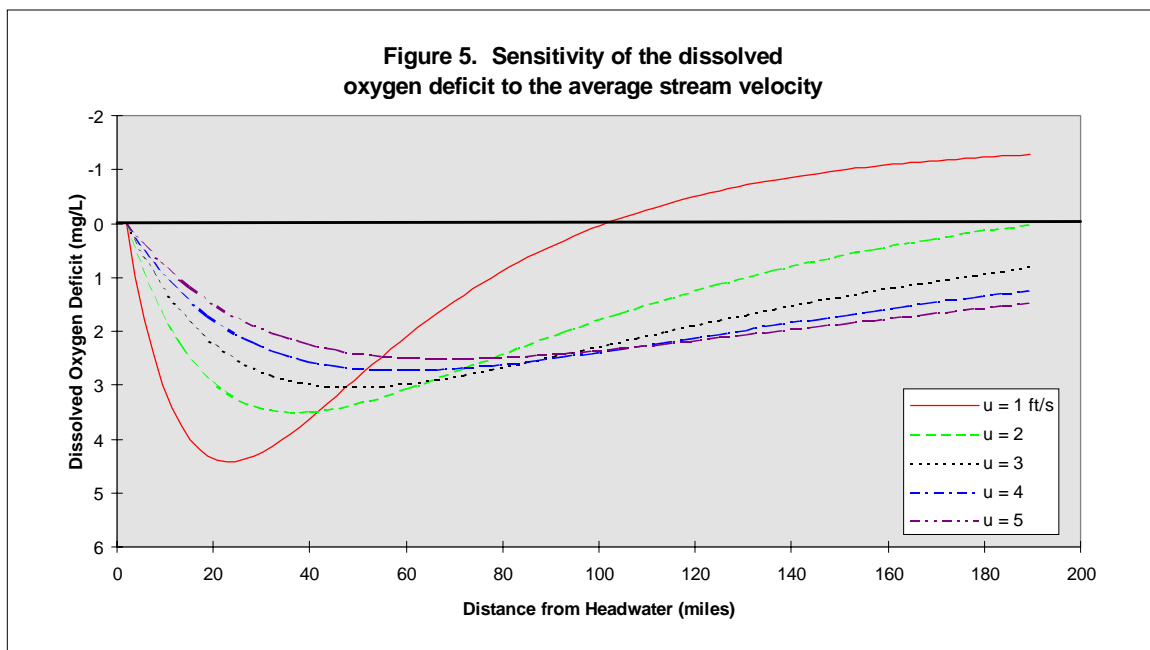
These terms were chosen because the coefficients of the dissolved oxygen equation and the CBOD and NBOD equations are functions of some or all of these terms. The sensitivity analyses of each of these terms are described in the following sections.

4.1.1 Average Stream Velocity

The average stream velocity is an important factor in both the reaeration coefficient and the time of travel along the stream. Examining Eqn.'s 13 and 14, we expect that as the velocity increases, the reaeration coefficient would also increase, resulting in an increased rate of oxygen transfer between the water and the atmosphere. The velocity also affects the spatial distribution of the dissolved oxygen, because an increased velocity results in a decreased travel time. Thus, the combined effect of these two relationships should result in a lower overall oxygen deficit due to the increased reaeration coefficient, with a more widespread effect of the dissolved oxygen deficit due to the decreased travel time.

STREADO was run with stream velocities ranging from 1 to 5 ft/s in order to investigate these effects of velocity on the DO deficit curve. The results shown in Figure 5 agree with our expectations. Here we see the characteristic DO sag curve, where the DO is decreasing as the BOD is being degraded, and then the DO begins to increase as the BOD oxygen sink becomes smaller than the reaeration and phytoplankton oxygen sources.

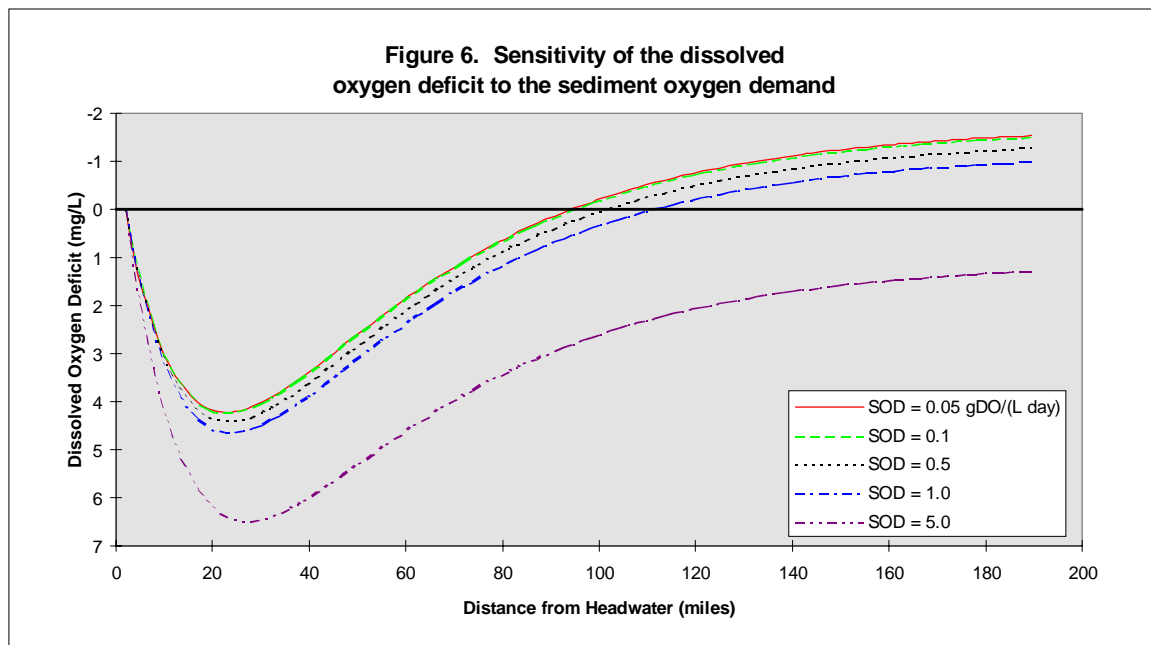
It is also seen in Figure 5 that for low velocities, after the BOD is degraded the phytoplankton produce enough oxygen to maintain super-saturated conditions. As the velocity increases, and thus the reaeration coefficient increases, the oxygen produced by the phytoplankton is released to the atmosphere at a higher rate, resulting in lower DO concentrations.



4.1.2 Areal Sediment Oxygen Demand

The areal sediment oxygen demand is an average distributed sediment oxygen demand throughout the stream reach. Therefore, as the areal SOD increases, we would expect the DO sag curve to drop and the DO to equilibrate to a lower value downstream, due to increased oxygen demand.

This analysis was performed on STREADO using areal SOD values ranging from 0.05 to 5.0 g-DO/(L-day). These values range from SOD values found in mineral soils to SOD values found at the outfall vicinity of municipal sewage sludge (Thomann and Mueller, Table 6.7). The results shown in Figure 6 indicate that the DO sag curve does indeed shift downward, and that the equilibrium values of the DO are lower with increasing SOD. It is also seen that after the BOD is degraded, the phytoplankton are able to produce enough oxygen to maintain the water at super-saturated conditions at low SOD values.

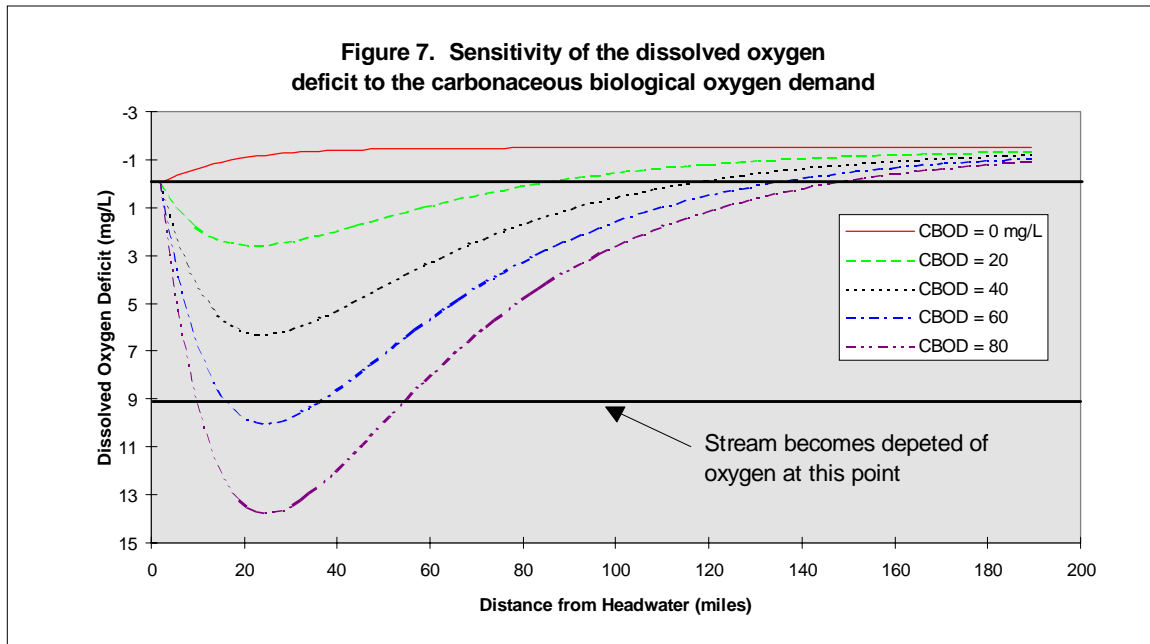


4.1.3 Biological Oxygen Demand

As discussed earlier, BOD is found in the form of both carbonaceous BOD and nitrogenous BOD. Both these forms of BOD affect the system in the same manner; therefore, only carbonaceous BOD is examined here.

Just as in the areal SOD, we would expect the DO sag curve to drop with increasing CBOD; however, since the CBOD is a point source term, and not a distributed term, the DO sag curve

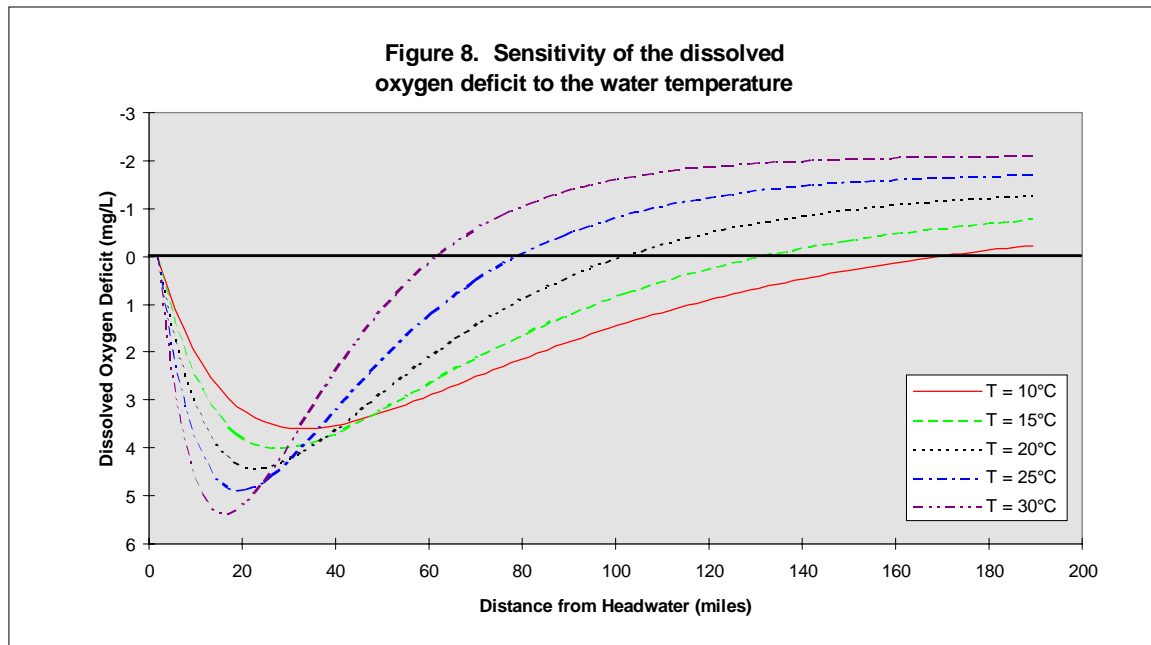
should equilibrate downstream to the same value, independent of the amount of CBOD at the point source. This is found in the results shown in Figure 7; as CBOD is ranged from 0 to 80 mg/L, the DO sag curve drops, but they all approach the same equilibrium value downstream. It is also seen in Figure 7 that the stream can go anaerobic given large CBOD influent concentrations (oxygen is totally depleted at a dissolved oxygen deficit of approximately 9 mg/L). It is interesting to note that as the BOD is degraded, the phytoplankton produce enough oxygen to maintain the system in super-saturated conditions.



4.1.4 Water Temperature

The water temperature affects all the terms of the DO and BOD equations. In general, decreased water temperature decreases the individual terms, but to different degrees. We would expect that as the temperature increases, the DO sag curve would drop faster due to the increased rate of BOD oxidation, and that it would recover faster and to a higher equilibrium level due to the increased oxygen production by the phytoplankton.

The results shown in Figure 8 agree with our expectations. Here the temperature was varied from 10 to 30°C; this range was chosen since the SOD temperature equation is not valid below 10°C (Thomann and Mueller, pg. 292). As seen in Figure 8, the DO sag curve is sharper with increasing temperature, and the downstream equilibrium value is increasing with increasing temperature.



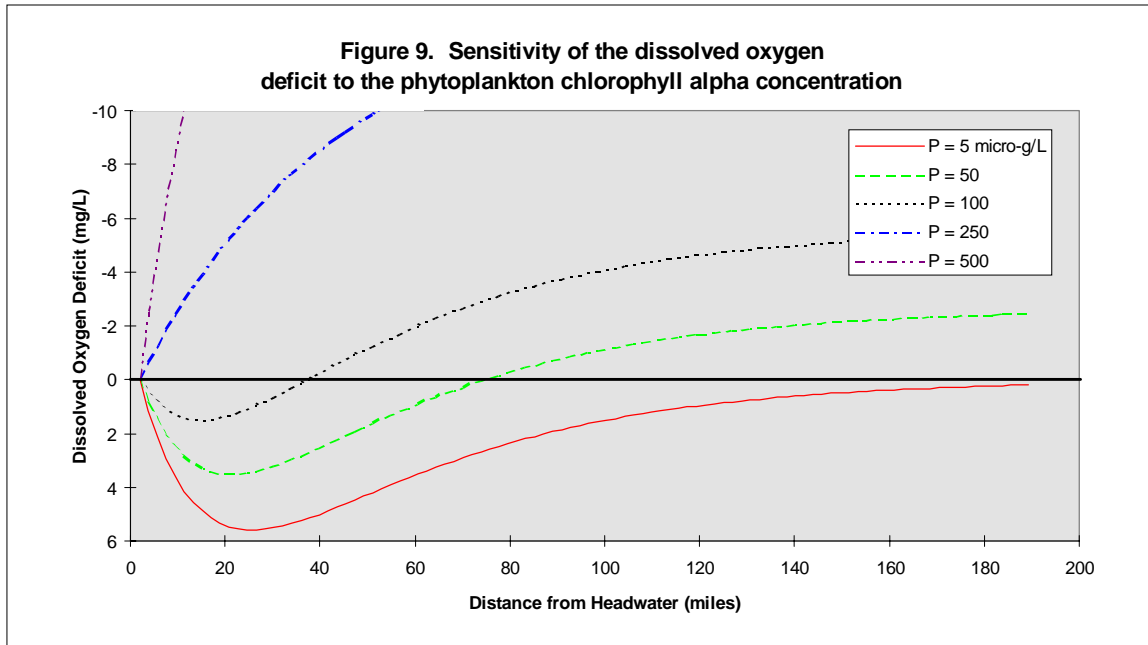
4.1.5 Phytoplankton Chlorophyll α Concentration

Due to the results of the prior analyses, which indicated that the phytoplankton oxygen production can result in super-saturated oxygen conditions, we expect the phytoplankton concentration to play a major role in the dissolved oxygen concentration in a stream. To analyze this, phytoplankton chlorophyll α concentrations were varied from 5 to 500 $\mu\text{g/L}$ in the stream reach (chlorophyll α concentrations as high as 250 $\mu\text{g/L}$ have been found in the Potomac Estuary; Thomann and Mueller, pg. 473). It is seen in Figure 9 that the dissolved oxygen concentration is extremely sensitive to the concentration of phytoplankton chlorophyll α present.

It must be pointed out that STREADO assumes a constant value of phytoplankton chlorophyll α , where in reality the phytoplankton chlorophyll α concentration is a function of the available nutrients. We can conclude from Figure 9 that to model phytoplankton chlorophyll α concentrations greater than 50 $\mu\text{g/L}$ require the addition of nutrient mass balances and variable phytoplankton growth based on the local nutrient concentrations.

4.1.6 Light Extinction Coefficient

The production of oxygen by the phytoplankton is a function of the light extinction coefficient. As the light extinction coefficient increases, the available light at a given depth is reduced, resulting in lower production of oxygen by the phytoplankton. Thus, for low light extinction coefficients, we expect the DO sag curve to drop moderately, with rapid recovery and high downstream equilibrium values due to the high oxygen production from the phytoplankton. As the light



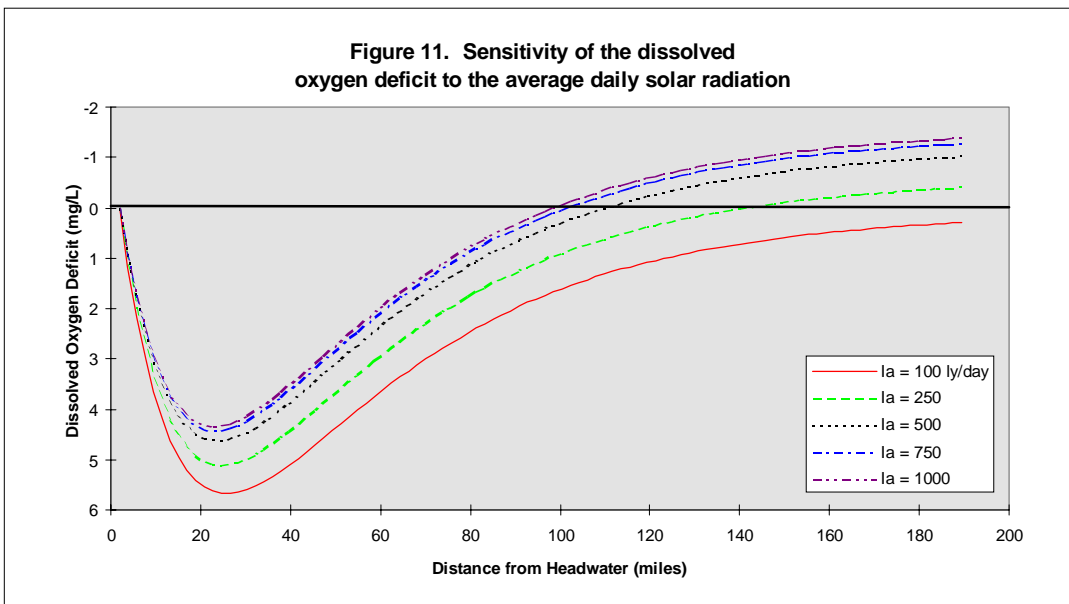
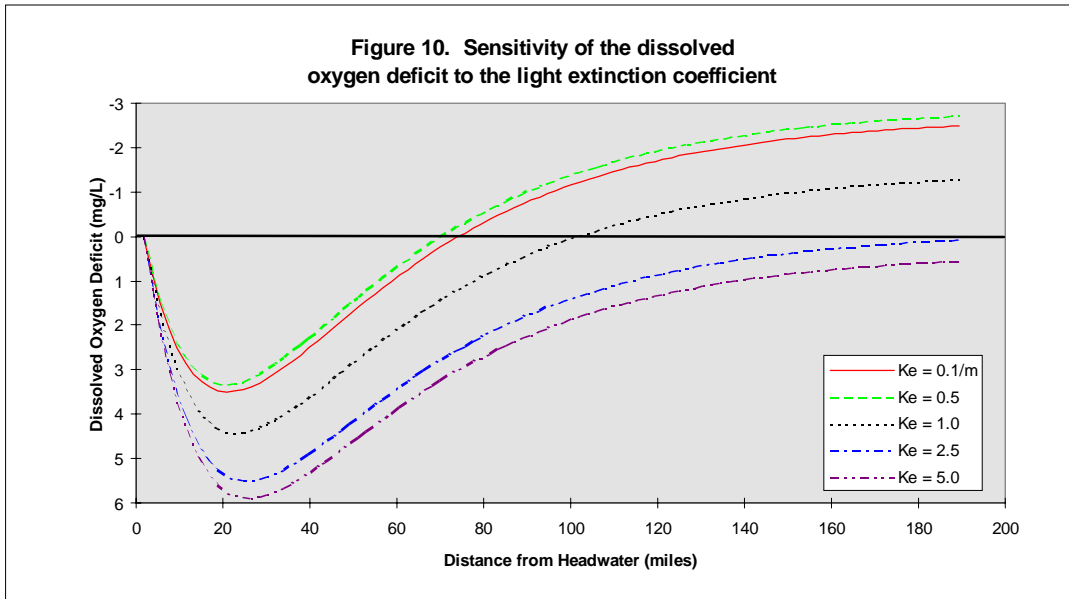
extinction coefficient increases, we expect the DO sag curve to drop lower, with longer recovery times and lower downstream equilibrium values. These expectations are born out by the results shown in Figure 10. Here the light extinction coefficient was ranged from 0.1 m^{-1} for clean water, to 5.0 m^{-1} for rather turbid water. K_e values as high as 6.9 m^{-1} have been reported for the Delaware river, and values up to 23 m^{-1} have been reported for sewage stabilization ponds (Thomann and Mueller, table 7.11).

4.1.7 Average Daily Solar Radiation

The phytoplankton oxygen production is driven by the available solar radiation. It is expected that the average daily solar radiation would affect the dissolved oxygen production in a similar manner to that of the light extinction coefficient - increasing average solar radiation would raise the DO sag curve due to increased oxygen production. This is indicated by the results shown in Figure 11, where the average daily solar radiation was varied from 100 to 1000 ly/day.

4.1.8 Average Water Depth

The reaeration term is a function of the water depth, along with the phytoplankton oxygen production through the light extinction coefficient. As the depth increases, the reaeration coefficient becomes smaller, and the volumetric amount of oxygen produced by the phytoplankton becomes smaller. It must be pointed out that since the BOD and phytoplankton chlorophyll α

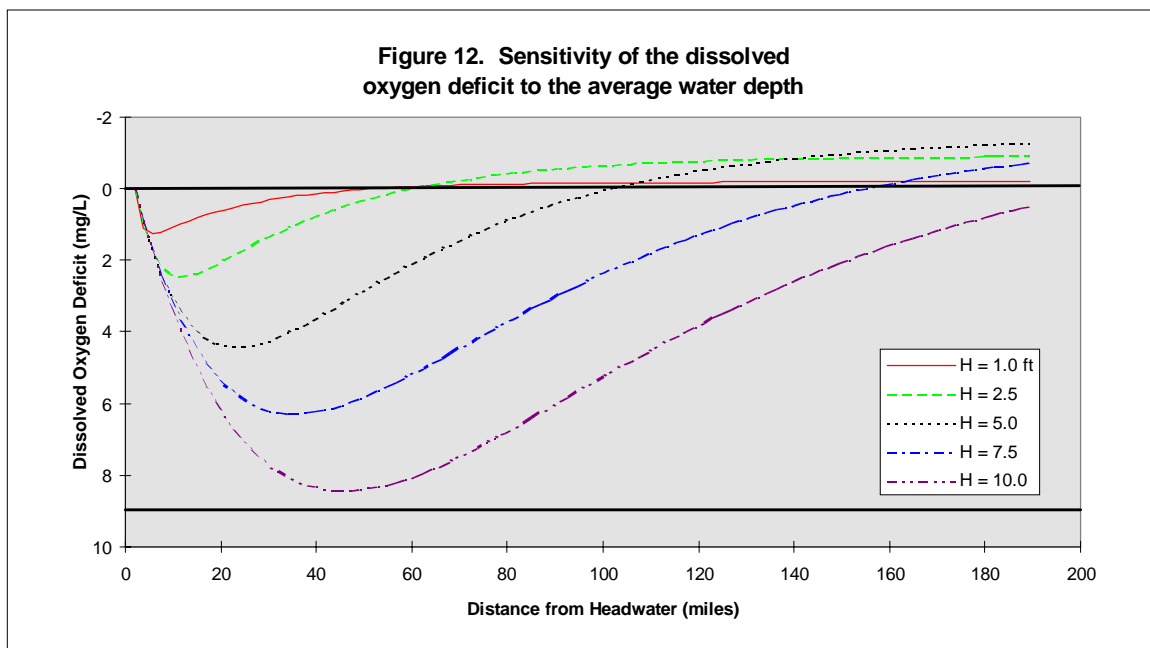


terms for this sensitivity analysis are given as concentrations at the headwater, the total mass of phytoplankton and BOD increase as the depth increases, due to the increasing volume of water.

Due to the effects of depth on the reaeration coefficient and phytoplankton oxygen production, and the constant BOD concentration at each depth, we would expect the following two results:

1. The DO sag curve should drop lower with increasing depth due to the lower reaeration coefficient and phytoplankton oxygen production.
2. The downstream equilibrium value of DO should increase with increasing depth due to the lower reaeration coefficient, as it takes longer for the oxygen produced by the phytoplankton to escape to the atmosphere.

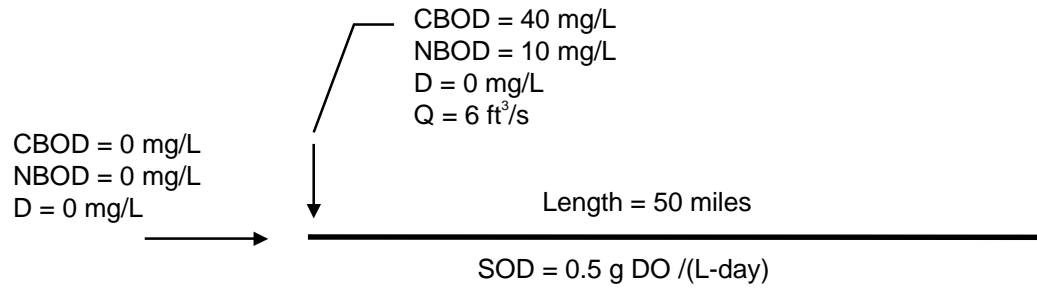
These expected results are indicated in Figure 12, where we see the drop in the DO sag curve and the higher downstream equilibrium value with increasing depth.



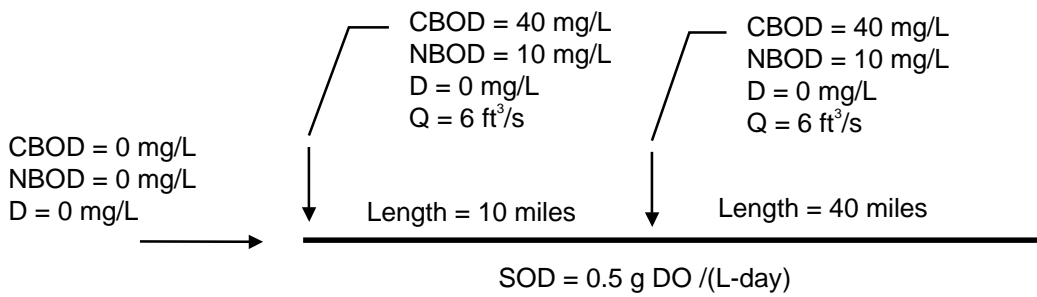
4.2 Case Studies

The sensitivity analyses in Section 4.1 provide a good look at how the individual terms affect the dissolved oxygen concentration. In order to determine how changes in conditions may affect a plausible scenario, two case studies were analyzed. These case studies examine a typical point source, representing effluent from a sewage treatment plant, discharging into a stream. The effects of this point source on the stream dissolved oxygen under three flow conditions (nominal, flood, and drought) were examined. The first case study looks at the effects of one sewage treatment plant, and the second case study examines the combined effects of a second identical

plant located 10 miles downstream from the first. Diagrams of the two cases are presented in Figure 13, and the baseline STREADO input files are included in Appendix B.



a. Single Point Source



b. Two Point Sources

Figure 13 - Case study diagrams

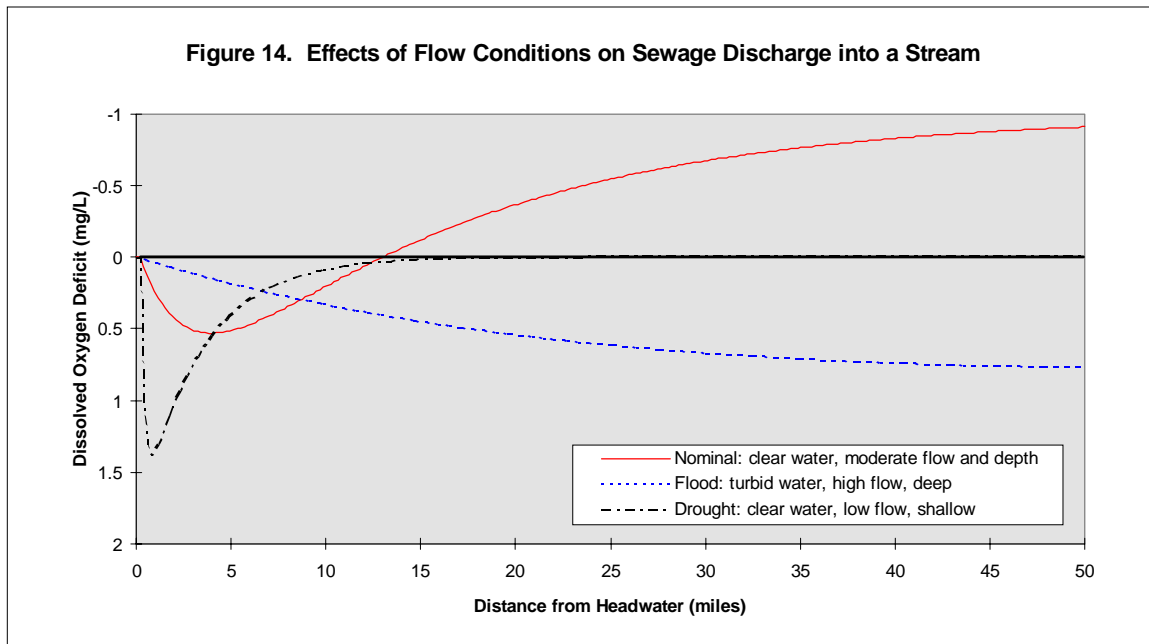
The stream conditions were modified for the three cases as follows:

	Flow Rate (cfs)	Velocity (ft/s)	Height (ft)	Light Extinction Coefficient (m^{-1})
Drought	5	0.2	0.5	1.0
Nominal	20	0.5	2.0	1.0
Flood	100	2.0	6.0	4.0

The results of these two case studies are presented below. Additionally, the results of the two nominal cases were compared to the Streeter-Phelps results to show the effects of the NBOD, photosynthesis, respiration, and SOD terms.

4.2.1 Effect of Flow Conditions on Single Point Source Discharge

The results of the single point source case are presented in Figure 14. The nominal case shows the expected DO sag curve, with the effects of the waste stream being felt for approximately 14 miles downstream of the outfall; at this point the stream becomes super-saturated due to the production of oxygen from the phytoplankton.



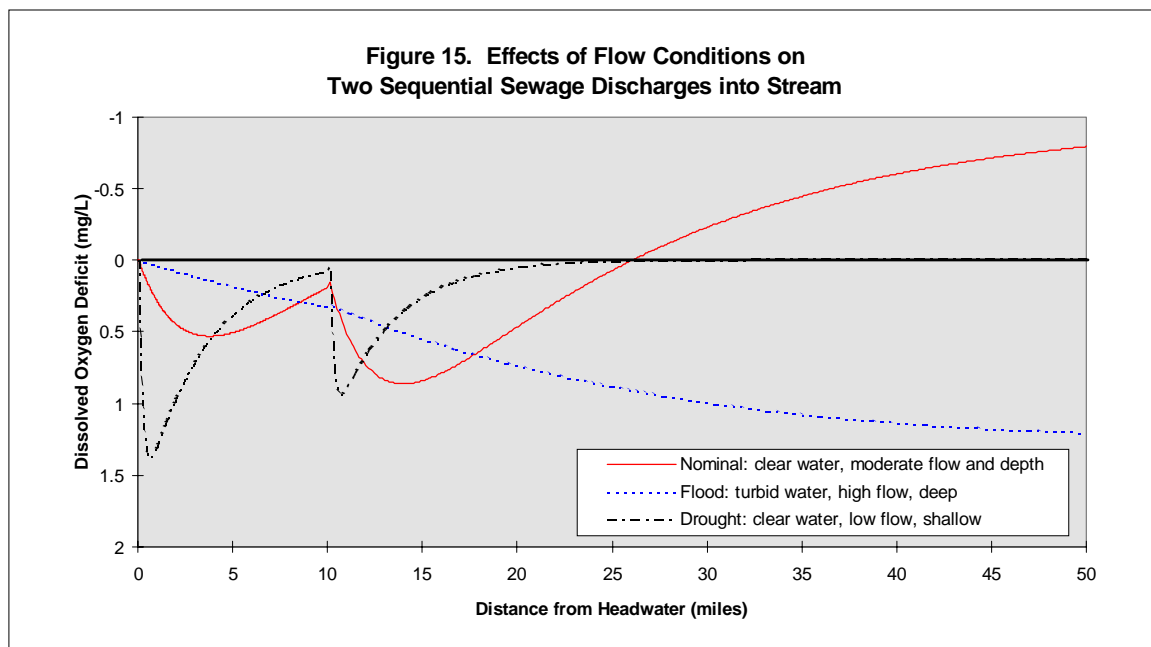
The drought case shows a substantial drop in the sag curve. This is due to the increased concentration of BOD in the stream resulting from the mixing of the waste stream with a lower stream flow. This drop in the sag curve could cause problems adjacent to the outfall if the dissolved oxygen concentration falls below the minimum standards set for the stream. It is seen that the effects of the waste stream are also negated approximately 14 miles downstream from the outfall. But here, due to the increased reaeration coefficient from the decreased depth, the DO equilibrates at a much lower concentration than in the nominal case.

The flood case shows interesting results. Due to the increased depth and high light extinction coefficient, very little oxygen gets into the system, resulting in a depressed sag curve.

Additionally, due to the increased velocity, the travel time has significantly decreased. These effects result in a depressed dissolved oxygen concentration much farther downstream than for either the nominal or drought cases. Thus, if there are other point sources downstream from the sewage treatment outfall, the combined effects could cause significant depression of the stream dissolved oxygen concentration.

4.2.2 Effect of Flow Conditions on Two Sequential Point Source Discharges

The results of the two point source discharges, presented in Figure 15, show the combined effects of a second sewage treatment plant ten miles downstream. This second outfall is located in the region affected by the first outfall. The results for the nominal case show the superposition of the sag curve from the first outfall on the sag curve from the second outfall, resulting in a lowered sag curve, shifted from zero by the remaining DO deficit from the first outfall.

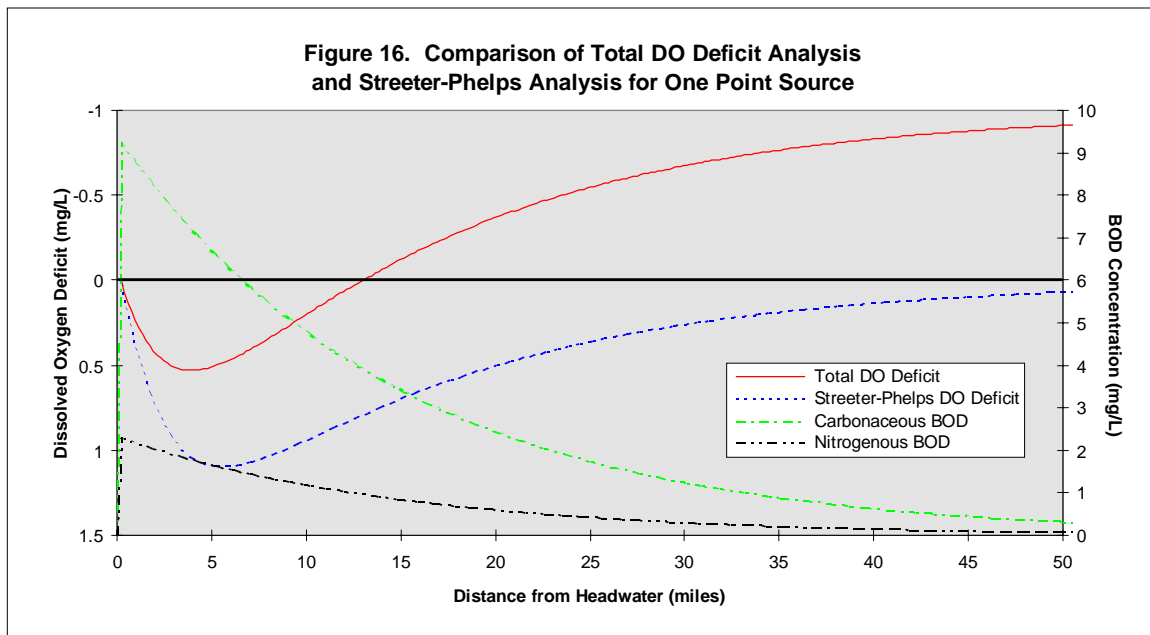


The drought case actually shows an improvement in the DO deficit at the second outfall. This is due to the increase in the stream flow rate from the addition of the first outflow; for the nominal and flood cases, this flow rate increase is negligible, but for the drought case where the flow rate is very low, this increase has significance.

The flood case shows a small change in the slope curve at the point of discharge. This second effluent stream results in a lower dissolved oxygen concentration farther downstream than for the single point source case.

4.2.3 Comparison of Streeter-Phelps Solution for Single Point Source Discharge

Figure 16 compares the results from the nominal one point source case with the Streeter-Phelps solution for the same case. It is seen that even with the inclusion of the NBOD and SOD terms in the total DO solution, the phytoplankton provide a significant source of oxygen to the stream.



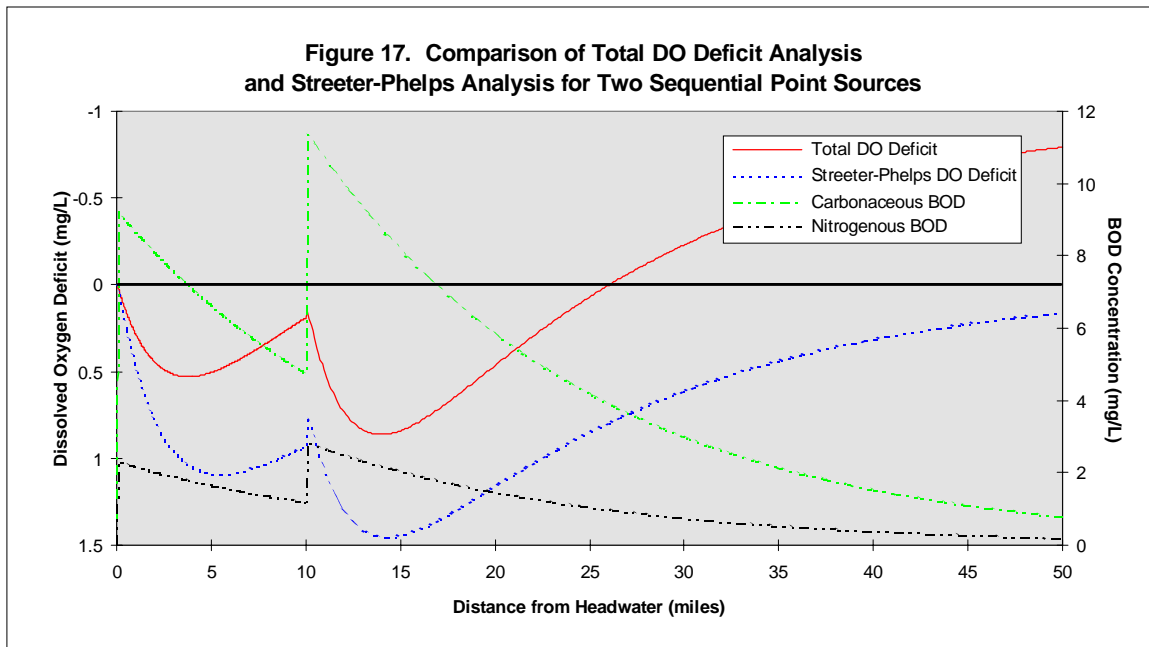
4.2.4 Comparison of Streeter-Phelps Solution for Two Sequential Point Source Discharges

Figure 17 compares the results from the nominal two point source case with the Streeter-Phelps solution for the same case. The conclusion here is the same as that for the one point source case: the phytoplankton provide a significant source of oxygen to the stream.

4.2.5 Case Study Conclusions

The following conclusions can be drawn from the case studies:

1. The dissolved oxygen deficit becomes zero at approximately the same distance downstream for both the nominal and drought conditions; however, the drought case results in a higher short term dissolved oxygen deficit. This



can cause problems if this dissolved oxygen concentration drops below specified levels for the stream.

2. The dissolved oxygen deficit is dependent on the distance between multiple waste stream inputs. This means that if a new waste input is proposed for a stream or river, both its BOD input and the proposed location with respect to other inputs are important in order to determine the effects on the stream dissolved oxygen level.
3. Discharge into flood waters results in decreased oxygen levels for a substantial distance downstream. This can have significant effects for streams and rivers with many influent waste streams over their course, as the dissolved oxygen will not have a chance to recover between each influent stream, resulting in significantly depressed oxygen levels.
4. The Streeter-Phelps equations can significantly underestimate the dissolved oxygen deficit of a stream.

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APPENDIX A
STREADO SOURCE CODE

```

/*

*****
Program:      STREADO.C
Developed By: Derick G. Brown
Date:        12 December 1994
*****

This program calculates the steady-state dissolved oxygen conditions
in a stream taking into account: (1) reaeration, (2) carbonaceous
biological oxygen demand (BOD - CBOD), (3) nitrogenous BOD (NBOD),
(4) phytoplankton photosynthesis, (5) phytoplankton respiration,
(6) sediment oxygen demand. STREADO allows multiple point sources
of CBOD, NBOD, and dissolved oxygen.

Mass balances are performed on the (1) dissolved oxygen deficit,
(2) Carbonaceous BOD, and (3) Nitrogenous BOD. STREADO assumes that
the stream is not nutrient limited, therefore STREADO also assumes that
the phytoplankton concentration remains constant (i.e., growth - death =
settling). If future editions of STREADO want to do a mass balance on
the phytoplankton concentration, then mass balances MUST also be
performed on the nutrients.

The equations for STREADO were taken from R.V. Thomann and J.A. Mueller,
"Principles of Surface Water Quality Modeling and Control", 1987,
Harper Collins Publishers, Inc. All equations taken from this book are
referenced by equation number and page number.

*/

/*****/
/* HEADERS */
/*****/

#include <stdio.h>
#include <math.h>
#include <stdlib.h>
#define ABS(x) ((x) < 0 ? -(x) : (x)) /* Absolute Value */
#define POWER(x,a) exp((a)*log((x))) /* x raised to the a power */
#define MAX_REACHES 10 /* maximum number of reaches */

/*****/
/* DEFINE STRUCTURES */
/*****/

/* coefficients */
struct T_COEFFICIENTS {
    double Ka; /* Reaeration coefficient [1/d] */
    double Kd; /* Effective deoxygenation rate [1/d] */
    double Kr; /* Overall loss rate [1/d] */
    double Kn; /* Nitrification rate [1/d] */
    double Pa; /* Average gross DO production [mg DO/(L day)] */
    double R; /* Respiration rate [mg DO/(L day)] */
    double Sb; /* Sediment oxygen demand [mg DO/(L day)] */
};

/* initial values */
struct T_INITIAL {
    double DO; /* Initial DO concentration [mg/L] */

```

```

    double CBOD;          /* Initial CBOD concentration [mg/L] */
    double NBOD;          /* Initial NBOD concentration [mg/L] */
};

/* stream parameters */
struct T_STREAM {
    double length;        /* length of reach [ft] */
    double velocity;     /* flow velocity [ft/s] */
    double depth;        /* average depth of stream [ft] */
    double flow;          /* flow rate [ft^3/s] */
    double temperature;  /* water temperature [deg C] */
    double areal_Sb;     /* areal sediment oxygen demand [g DO/(m^2 d)] */
};

/* phytoplankton variables */
struct T_PHYTOPLANKTON {
    double P;             /* phytoplankton chlorophyl [micro-g/L] */
    double Ke;           /* extinction coefficient [1/m] */
    double Ia;           /* average daily solar radiation [ly/day] */
    double Is;           /* rad. at max. phytoplankton growth [ly/day] */
    double f;            /* photoperiod (duration of light) [day] */
    double aop;          /* ratio (mg DO)/(micro-g chlorophyl alpha) */
    double Gmax;         /* maximum growth rate [1/d] */
};

/* operational data */
struct T_OPERATIONAL {
    double dx;           /* x increment [ft] */
    int nsteps;          /* number of steps to loop x over */
};

/*****
/* FUNCTION PROTOTYPES */
*****/

void QUERY_USER(
    char *input_file[],
    char *output_file[]);

void READ_DATA(
    char input_file[50],
    int *nreaches_ptr,
    struct T_STREAM *stream_ptr,
    struct T_PHYTOPLANKTON *phyto_ptr,
    struct T_OPERATIONAL *oper_ptr,
    struct T_INITIAL *initial_ptr,
    struct T_COEFFICIENTS *coeff_ptr);

void INITIALIZE_PARAMETERS(
    int nreaches,
    const struct T_STREAM *stream_ptr,
    struct T_OPERATIONAL *oper_ptr);

double CALC_Ka(
    struct T_STREAM stream_data);

double CALC_Kd(
    struct T_STREAM stream_data);

```

```
double CALC_Kn(
    struct T_STREAM stream_data);

double CALC_Pa(
    struct T_STREAM stream_data,
    struct T_PHYTOPLANKTON phyto_data);

double CALC_R(
    struct T_STREAM stream_data,
    struct T_PHYTOPLANKTON phyto_data);

double CALC_Sb(
    struct T_STREAM stream_data);

void CALC_COEFFICIENTS(
    int nreaches,
    const struct T_STREAM *stream_ptr,
    const struct T_PHYTOPLANKTON *phyto_ptr,
    struct T_COEFFICIENTS *coeff_ptr);

double DO_EQUATION(
    double t,
    struct T_INITIAL initial_data,
    struct T_COEFFICIENTS coefficients);

double CBOD_EQUATION(
    double t,
    struct T_INITIAL initial_data,
    struct T_COEFFICIENTS coefficients);

double NBOD_EQUATION(
    double t,
    struct T_INITIAL initial_data,
    struct T_COEFFICIENTS coefficients);

void CALC_PROFILE(
    int nreaches,
    const struct T_OPERATIONAL *oper_ptr,
    const struct T_STREAM *stream_ptr,
    const struct T_INITIAL *initial_ptr,
    const struct T_COEFFICIENTS *coeff_ptr,
    double *DO_ptr,
    double *CBOD_ptr,
    double *NBOD_ptr);

double MIX_IT(
    double flow1,
    double flow2,
    double component1,
    double component2);

void CALC_SP_COEFFICIENTS(
    int nreaches,
    const struct T_COEFFICIENTS *coeff_ptr,
    struct T_COEFFICIENTS *SP_coeff_ptr);

void WRITE_DO_PROFILE(
    char out_file[50],
    int nreaches,
    const struct T_OPERATIONAL *oper_ptr,
    const double *DO_ptr,
    const double *CBOD_ptr,
    const double *NBOD_ptr,
```

```

    const double *SP_ptr);

/*****
/* MAIN CODE */
*****/

main ()
{
    /* Define input variables */
    struct T_STREAM stream_data[MAX_REACHES];          /* stream variables */
    struct T_PHYTOPLANKTON phyto_data[MAX_REACHES];   /* phytoplankton data */
    struct T_OPERATIONAL oper_data[MAX_REACHES];     /* operational data */
    struct T_INITIAL initial_data[MAX_REACHES];      /* initial values */
    struct T_COEFFICIENTS coefficients[MAX_REACHES]; /* rate coefficients */
    int nreaches;                                     /* number of reaches */

    /* Define internal variables */
    struct T_COEFFICIENTS SP_coeff[MAX_REACHES];     /* Streeter-Phelps coefficients */
    char input_file[50];                             /* input file name */
    char output_file[50];                           /* output file name */
    int total_steps;                                 /* total number of steps */
    int reach;                                       /* reach counter */

    /* Define output variables */
    double *DO_ptr;    /* pointer to array of Dissolved Oxygen Deficit */
    double *CBOD_ptr;  /* pointer to array of CBOD concentration */
    double *NBOD_ptr;  /* pointer to array of NBOD cocntration */
    double *SP_ptr;    /* pointer to array of Streeter-Phelps DO def. */
    double *DC_ptr;    /* pointer to dummy CBOD array */
    double *DN_ptr;    /* pointer to dummy NBOD array */

    /* Get Filenames */
    QUERY_USER(
        &input_file,
        &output_file);

    /* Read in Data */
    READ_DATA(
        input_file,
        &nreaches,          /* passing address */
        stream_data,       /* passing address of first array element */
        phyto_data,        /* passing address of first array element */
        oper_data,         /* passing address of first array element */
        initial_data,      /* passing address of first array element */
        coefficients);     /* passing address of first array element */

    /* calculate the total number of steps */
    for (reach = 0, total_steps = 0; reach < nreaches; reach++)
        total_steps += oper_data[reach].nsteps;

    /* Allocate dymanic memory for output arrays */
    DO_ptr = (double *) malloc(total_steps * sizeof(double));

```

```

if (DO_ptr == NULL){
    puts ("ERROR: Out of Memory");
    exit (1);
}; /* end if */
CBOD_ptr = (double *) malloc(total_steps * sizeof(double));
if (CBOD_ptr == NULL){
    puts ("ERROR: Out of Memory");
    exit (1);
}; /* end if */
NBOD_ptr = (double *) malloc(total_steps * sizeof(double));
if (NBOD_ptr == NULL){
    puts ("ERROR: Out of Memory");
    exit (1);
}; /* end if */
SP_ptr = (double *) malloc(total_steps * sizeof(double));
if (SP_ptr == NULL){
    puts ("ERROR: Out of Memory");
    exit (1);
}; /* end if */
DC_ptr = (double *) malloc(total_steps * sizeof(double));
if (DC_ptr == NULL){
    puts ("ERROR: Out of Memory");
    exit (1);
}; /* end if */
DN_ptr = (double *) malloc(total_steps * sizeof(double));
if (DN_ptr == NULL){
    puts ("ERROR: Out of Memory");
    exit (1);
}; /* end if */

/* Initialize Parameters */
INITIALIZE_PARAMETERS(
    nreaches,
    stream_data,          /* passing address of first array element */
    oper_data);          /* passing address of first array element */

/* Calculate Coefficients */
CALC_COEFFICIENTS(
    nreaches,
    stream_data,
    phyto_data,
    coefficients);      /* passing address of first array element */

/* Determine profile */
CALC_PROFILE(
    nreaches,
    oper_data,
    stream_data,
    initial_data,
    coefficients,
    DO_ptr,              /* passing address of first array element */
    CBOD_ptr,           /* passing address of first array element */
    NBOD_ptr);          /* passing address of first array element */

/* Determine Streeter-Phelps coefficients */
CALC_SP_COEFFICIENTS(
    nreaches,
    coefficients,
    SP_coeff);          /* passing address of first array element */

```

```

/* Determine Streeter-Phelps DO profile */
CALC_PROFILE(
    nreaches,
    oper_data,
    stream_data,
    initial_data,
    SP_coeff,
    SP_ptr,           /* passing address of first array element */
    DC_ptr,           /* passing address of first array element */
    DN_ptr);         /* passing address of first array element */

/* Output Results */
WRITE_DO_PROFILE(
    output_file,
    nreaches,
    oper_data,
    DO_ptr,           /* passing address of first array element */
    CBOD_ptr,        /* passing address of first array element */
    NBOD_ptr,        /* passing address of first array element */
    SP_ptr);         /* passing address of first array element */

} /* end of main */

/*****
/* QUERY_USER: This subroutine queries the user for the input and
/*              output file names.
*****/

void QUERY_USER(
    char *input_file[],
    char *output_file[])
{
    /* print title block */
    puts(" ");
    puts(" ");
    puts("-----");
    puts("Stream Reach Dissolved Oxygen Analysis (STREADO.C)");
    puts("Developed by: Derick G. Brown");
    puts("Date: 12 December 1994");
    puts("-----");
    puts(" ");

    /* get input file name */
    printf("Enter input filename: ");
    gets(input_file);

    /* get output file name */
    printf("Enter output filename: ");
    gets(output_file);
    puts(" ");

```

```

} /* end QUERY_USER */

/*****
/* READ_DATA: This subroutine reads the data found in input_file. */
*****/

void READ_DATA(
    char input_file[50],
    int *nreaches_ptr,
    struct T_STREAM *stream_ptr,
    struct T_PHYTOPLANKTON *phyto_ptr,
    struct T_OPERATIONAL *oper_ptr,
    struct T_INITIAL *initial_ptr,
    struct T_COEFFICIENTS *coeff_ptr)
{

    /* define file pointer */
    FILE *infile;

    /* define internal variables */
    int reach;          /* reach counter */
    int cur_reach;     /* current reach number */
    int count;         /* loop counter */
    double P;          /* constant phytoplankton value */
    double temp;       /* constant temperature value */
    double Is;         /* constant solar radiation at max growth */
    double f;          /* constant photoperiod */
    double aop;        /* constant DO/chorophyl alpha ratio */
    double Gmax;       /* constant maximum growth rate */

    /* open input file */
    if ((infile = fopen(input_file,"r")) == NULL ) {
        puts ("ERROR: Cannot open input file \n");
        exit (1);
    }; /* end if */

    /* rewind the file */
    rewind(infile);

    /* read three blank lines */
    fscanf(infile,"%*[\n]*c");
    fscanf(infile,"%*[\n]*c");
    fscanf(infile,"%*[\n]*c");

    /* read number of reaches */
    fscanf(infile,"%d%*[\n]*c",nreaches_ptr);

    /* error if nreaches < 0 or > MAX_REACHES */
    if ((*nreaches_ptr <= 0) || (*nreaches_ptr > MAX_REACHES)) {
        puts("ERROR: Invalid number of reaches.");
        printf("      Must be > 0 and <= %d\n",MAX_REACHES);
        exit(1);
    }; /* end if */

    /* read in constant values */
    fscanf(infile,"%lf%*[\n]*c",&temp);
    fscanf(infile,"%lf%*[\n]*c",&P);
    fscanf(infile,"%lf%*[\n]*c",&Is);

```

```

fscanf(infile, "%lf%*[\n]*c", &f);
fscanf(infile, "%lf%*[\n]*c", &aop);
fscanf(infile, "%lf%*[\n]*c", &Gmax);

/* loop over number of reaches */
for (reach = 0; reach < *nreaches_ptr; reach++) {

    /* read blank line */
    fscanf(infile, "%*[\n]*c");

    /* read reach number */
    fscanf(infile, "%^[0123456789]%d%*[\n]*c", &cur_reach);

    /* make sure reach number correct */
    if (cur_reach != reach) {
        puts("ERROR: Reaches numbered incorrectly.");
        puts("      Reaches must start at zero and be numbered sequentially.");
        exit (1);
    }; /* end if */

    fscanf(infile, "%lf%*[\n]*c", &(stream_ptr->length));
    fscanf(infile, "%lf%*[\n]*c", &(stream_ptr->velocity));
    fscanf(infile, "%lf%*[\n]*c", &(stream_ptr->depth));
    fscanf(infile, "%lf%*[\n]*c", &(stream_ptr->flow));
    fscanf(infile, "%lf%*[\n]*c", &(coeff_ptr->Ka));
    fscanf(infile, "%lf%*[\n]*c", &(coeff_ptr->Kd));
    fscanf(infile, "%lf%*[\n]*c", &(coeff_ptr->Kr));
    fscanf(infile, "%lf%*[\n]*c", &(coeff_ptr->Kn));
    fscanf(infile, "%lf%*[\n]*c", &(coeff_ptr->Pa));
    fscanf(infile, "%lf%*[\n]*c", &(coeff_ptr->R));
    fscanf(infile, "%lf%*[\n]*c", &(coeff_ptr->Sb));
    stream_ptr->temperature = temp; /* currently a const. value */
    fscanf(infile, "%lf%*[\n]*c", &(stream_ptr->areal_Sb));
    phyto_ptr->P = P; /* currently a const. value */
    fscanf(infile, "%lf%*[\n]*c", &(phyto_ptr->Ke));
    fscanf(infile, "%lf%*[\n]*c", &(phyto_ptr->Ia));
    phyto_ptr->Is = Is; /* currently a const. value */
    phyto_ptr->f = f; /* currently a const. value */
    phyto_ptr->aop = aop; /* currently a const. value */
    phyto_ptr->Gmax = Gmax; /* currently a const. value */
    fscanf(infile, "%d%*[\n]*c", &(oper_ptr->nsteps));
    fscanf(infile, "%lf%*[\n]*c", &(initial_ptr->DO));
    fscanf(infile, "%lf%*[\n]*c", &(initial_ptr->CBOD));
    fscanf(infile, "%lf%*[\n]*c", &(initial_ptr->NBOD));

    /* increment reach array pointers */
    stream_ptr++;
    coeff_ptr++;
    phyto_ptr++;
    oper_ptr++;
    initial_ptr++;

}; /* end for */

/* close file */
fclose (infile);

/* write status */
puts("Data read in successfully");

} /* end READ_DATA */

```

```

/*****
/* INITIALIZE_PARAMETERS: This function initializes any required
/*
/* parameters.
/*
/*****

void INITIALIZE_PARAMETERS(
    int nreaches,
    const struct T_STREAM *stream_ptr,
    struct T_OPERATIONAL *oper_ptr)
{
    /* internal variables */
    int reach;

    /* loop over number of reaches */
    for (reach = 0; reach < nreaches; reach++) {

        /* determine dx value */
        oper_ptr->dx = (stream_ptr->length)/(oper_ptr->nsteps);

        /* increment reach array pointers */
        oper_ptr++;
        stream_ptr++;

    }; /* end for */
} /* end INITIALIZE_PARAMETERS */

/*****
/* CALC_Ka: This function calculates the reaeration coefficient.
/*
/* Ka is calculated from Eqn. 6.26 (pg 280) and Eqn. 6.32
/*
/* (pg 282). The units of Ka are [1/d].
/*
/*****

double CALC_Ka(
    struct T_STREAM stream_data)
{
    /* Internal variables */
    double Ka20; /* reaeration coefficient at 20 deg C */
    double theta; /* temperature coefficient */

    /* Calculate reaeration coefficient for 20 degrees C */
    if (stream_data.velocity < 1.8) {

        /* Use theoretical equation */
        Ka20 = 12.9*
            POWER(stream_data.velocity, 0.5)*
            POWER(stream_data.depth, -1.5);

    } else {

        /* Use empirical equation */

```

```

        Ka20 = 11.6*(stream_data.velocity)*
            POWER(stream_data.depth,-1.67);

}; /* end if */

/* Define theta (pg 282) */
theta = 1.024;

/* Correct for temperature and return value */
return Ka20*POWER(theta,(stream_data.temperature - 20.0));

} /* end CALC_Ka */

/*****
/* CALC_Kd: This function calculates the effective deoxygenation
/* rate. Kd is calculated from Eqn. 6.60 (pg 296) and
/* Eqn. 6.62 (pg 298). The units of Kd are [1/d].
*****/

double CALC_Kd(
    struct T_STREAM stream_data)
{
    /* Internal variables */
    double Kd20; /* reaeration coefficient at 20 deg C */
    double theta; /* temperature coefficient */

    /* Calculate Kd for 20 degrees C */
    if (stream_data.depth <= 8.0) {
        Kd20 = 0.3*POWER((stream_data.depth/8.0),-0.434);
    } else {
        Kd20 = 0.3;
    }; /* end if */

    /* Define theta */
    theta = 1.047;

    /* Correct for temperature and return value */
    return Kd20*POWER(theta,(stream_data.temperature - 20.0));

} /* end CALC_Kd */

/*****
/* CALC_Kn: This function calculates the nitrification rate. Kn
/* is calculated from Eqn. 6.60 (pg 296) and Eqn. 6.71
/* (pg 301). The units of Kn are [1/d].
*****/

double CALC_Kn(
    struct T_STREAM stream_data)
{
    /* Internal variables */

```

```

double Kn20;      /* Nitrification rate at 20 deg C */
double theta;    /* temperature coefficient */

/* Calculate Kn for 20 degrees C */
if (stream_data.depth <= 8.0) {
    Kn20 = 0.3*POWER((stream_data.depth/8.0),-0.434);
} else {
    Kn20 = 0.3;
}; /* end if */

/* Define theta */
theta = 1.08;

/* Correct for temperature and return value */
return Kn20*POWER(theta,(stream_data.temperature - 20.0));

} /* end CALC_Kn */

/*****/
/* CALC_Pa: This function calculates the DO production rate from      */
/*          photosynthesis. Pa is calculated from Eqns. 6.40-41      */
/*          (pg 287) The units of Pa are [mg DO/(L day)]. Note      */
/*          we assume that phytoplankton growth is not nutrient     */
/*          limited.                                                */
/*****/

double CALC_Pa(
    struct T_STREAM stream_data,
    struct T_PHYTOPLANKTON phyto_data)
{
    /* Internal variables */
    double GIa;      /* Light attenuation factor */
    double alpha_0; /* intermediate variable */
    double alpha_1; /* intermediate variable */
    double theta;   /* temperature coefficient */

    /* calculate alpha_0 */
    alpha_0 = phyto_data.Ia/phyto_data.Is;

    /* calculate alpha_1 */
    alpha_1 = alpha_0*exp(-stream_data.depth*phyto_data.Ke);

    /* calculate GIa */
    GIa = 2.718*phyto_data.f*(exp(-alpha_1) - exp(-alpha_0))/
        (stream_data.depth*phyto_data.Ke);

    /* Define theta */
    theta = 1.066;

    /* Correct for temperature and return value */
    return phyto_data.Gmax*GIa*phyto_data.aop*phyto_data.P*
        POWER(theta, (stream_data.temperature - 20.0));

} /* end CALC_Pa */

```

```

/*****
/* CALC_R: This function calculates the DO utilization rate from
/*      respiration. R is calculated from Eqn. 6.43 (pg 290).
/*      The units of R are [mg DO/(L day)].
*****/

double CALC_R(
    struct T_STREAM stream_data,
    struct T_PHYTOPLANKTON phyto_data)
{
    /* Internal variables */
    double theta; /* temperature coefficient */

    /* Define theta */
    theta = 1.08;

    /* Correct for temperature and return value */
    return phyto_data.aop*phyto_data.P*0.1*
        POWER(theta, (stream_data.temperature - 20.0));
} /* end CALC_R */

/*****
/* CALC_Sb: This function calculates the rate of oxygen utilization
/*      from the sediment. Sb is calculated from Eqn. 6.49
/*      (pg 292). The units of Sb are [mg DO/(L day)].
/*      Note that g/m^3 = mg/L.
*****/

double CALC_Sb(
    struct T_STREAM stream_data)
{
    /* Internal variables */
    double theta; /* temperature coefficient */
    double conversion; /* conversion factor */

    /* Define theta */
    theta = 1.065;

    /* Correct for temperature and return value */
    /* Note that we convert depth to meters, and that */
    /* g/m^2 = mg/L */
    return stream_data.areal_Sb/(stream_data.depth*0.3048)*
        POWER(theta, (stream_data.temperature - 20.0));
} /* end CALC_Sb */

```

```

/*****
/* CALC_COEFFICIENTS: This subroutine calculates the various      */
/*      coefficients.  If the value of the coefficients read in  */
/*      from the data file are negative, then we are to        */
/*      calculate the values; if they are greather than zero,  */
/*      then the user has supplied them.                        */
/*****

void CALC_COEFFICIENTS(
    int nreaches,
    const struct T_STREAM *stream_ptr,
    const struct T_PHYTOPLANKTON *phyto_ptr,
    struct T_COEFFICIENTS *coeff_ptr)
{
    /* define function return values */
    double CALC_Ka();
    double CALC_Kd();
    double CALC_Kr();
    double CALC_Kn();
    double CALC_Pa();
    double CALC_R();
    double CALC_Sb();

    /* define reach counter */
    int reach;

    /* loop over the number of reaches */
    for (reach = 0; reach < nreaches; reach++) {

        /* determine reaeration coeff */
        if (coeff_ptr->Ka < 0.0) coeff_ptr->Ka = CALC_Ka(*stream_ptr);

        /* error trap on Ka, since it is the denominator in a number of eqns */
        if (ABS(coeff_ptr->Ka) < 1.0e-30) {
            printf("ERROR: Ka[%d] is approximately zero.\n",reach);
            exit(1);
        }; /* end if */

        /* determine the effective deoxygenation rate */
        if (coeff_ptr->Kd < 0.0) coeff_ptr->Kd = CALC_Kd(*stream_ptr);

        /* determine the overall loss rate (we assume Ks = 0) */
        if (coeff_ptr->Kr < 0.0) coeff_ptr->Kr = coeff_ptr->Kd;

        /* determine the nitrification rate */
        if (coeff_ptr->Kn < 0.0) coeff_ptr->Kn = CALC_Kn(*stream_ptr);

        /* determine the DO production rate from phytoplankton */
        if (coeff_ptr->Pa < 0.0)
            coeff_ptr->Pa = CALC_Pa(*stream_ptr, *phyto_ptr);

        /* determine the respiration rate */
        if (coeff_ptr->R < 0.0)
            coeff_ptr->R = CALC_R(*stream_ptr, *phyto_ptr);

        /* determine the sediment oxygen demand rate */
        if (coeff_ptr->Sb < 0.0) coeff_ptr->Sb = CALC_Sb(*stream_ptr);

        /* increment reach array pointers */
        stream_ptr++;
        coeff_ptr++;
    }
}

```

```

    phyto_ptr++;

}; /* end for */

/* write status */
puts("Coefficients calculated");

} /* end CALC_COEFFICIENTS */

/*****
/* CALC_SP_COEFFICIENTS: This subroutine calculates the STREETER-
/*      Phelps coefficients.
*****/

void CALC_SP_COEFFICIENTS(
    int nreaches,
    const struct T_COEFFICIENTS *coeff_ptr,
    struct T_COEFFICIENTS *SP_coeff_ptr)
{
    /* define reach counter */
    int reach;

    /* loop over number of reaches */
    for (reach = 0; reach < nreaches; reach++) {

        /* define Streeter-Phelps coefficients */
        SP_coeff_ptr->Ka = coeff_ptr->Ka;
        SP_coeff_ptr->Kd = coeff_ptr->Kd;
        SP_coeff_ptr->Kr = coeff_ptr->Kr;
        SP_coeff_ptr->Kn = 0.0;
        SP_coeff_ptr->Pa = 0.0;
        SP_coeff_ptr->R = 0.0;
        SP_coeff_ptr->Sb = 0.0;

        /* increment array pointers */
        SP_coeff_ptr++;
        coeff_ptr++;

    }; /* end for */

} /* end CALC_SP_COEFFICIENTS */

/*****
/* DO_EQUATION: This function returns the value of dissolved oxygen
/*      at distance x along the stream, as given by Eqn.
/*      6.106 (pg 322), where x is given in feet from the
/*      point source.
*****/

double DO_EQUATION(
    double t,
    struct T_INITIAL initial_data,
    struct T_COEFFICIENTS coefficients)
{

```

```

/* define rate variables */
double Ka; /* reaeration rate [1/d] */
double Kd; /* deoxygenation rate [1/d] */
double Kr; /* overall loss rate [1/d] */
double Kn; /* nitrification rate [1/d] */
double Pa; /* phytosynthesis rate [mg DO/(L d)] */
double R; /* respiration rate [mg DO/(L d)] */
double Sb; /* SOD rate [mg DO/(L d)] */

/* define common exponential term */
double common;

/* define individual DO equation terms */
double reaeration;
double carbonaceous_BOD;
double nitrogenous_BOD;
double phytosynthesis;
double respiration;
double sediment;

/* get coefficients */
Ka = coefficients.Ka;
Kd = coefficients.Kd;
Kr = coefficients.Kr;
Kn = coefficients.Kn;
Pa = coefficients.Pa;
R = coefficients.R;
Sb = coefficients.Sb;

/* calculate the common exponential term */
common = exp(-Ka*t);

/* calculate reaeration term */
reaeration = initial_data.DO*common;

/* calculate the CBOD term */
carbonaceous_BOD = initial_data.CBOD*Kd/(Ka - Kr)*(exp(-Kr*t) - common);

/* calculate the NBOD term */
nitrogenous_BOD = initial_data.NBOD*Kn/(Ka - Kn)*(exp(-Kn*t) - common);

/* calculate the phytosynthesis term */
phytosynthesis = Pa/Ka*(1 - common);

/* calculate the respiration term */
respiration = R/Ka*(1 - common);

/* calculate the SOD term */
sediment = Sb/Ka*(1 - common);

/* Put it all together */
return (reaeration + carbonaceous_BOD + nitrogenous_BOD -
        phytosynthesis + respiration + sediment);
} /* end DO_EQUATION */

```

```

/*****
/* CBOD_EQUATION: This function returns the value of CBOD at a      */
/*      distance x along the stream, as given by Eqn. 6.74      */
/*      (pg 302), where x is given in feet from the point      */
/*      point.                                                  */
/*****

double CBOD_EQUATION(
    double t,
    struct T_INITIAL initial_data,
    struct T_COEFFICIENTS coefficients)
{
    /* calculate the CBOD term and return*/
    return initial_data.CBOD*exp(-coefficients.Kr*t);
} /* end CBOD_EQUATION */

/*****
/* NBOD_EQUATION: This function returns the value of NBOD at a      */
/*      distance x along the stream, as given by Eqn. 6.94      */
/*      (pg 314), where x is given in feet from the point      */
/*      point.                                                  */
/*****

double NBOD_EQUATION(
    double t,
    struct T_INITIAL initial_data,
    struct T_COEFFICIENTS coefficients)
{
    /* calculate the NBOD term and return*/
    return initial_data.NBOD*exp(-coefficients.Kn*t);
} /* end CBOD_EQUATION */

/*****
/* CALC_PROFILE: This subroutine uses DO_EQUATION to create a      */
/*      profile of dissolved oxygen versus distance for the      */
/*      stream reach being examined.                            */
/*****

void CALC_PROFILE(
    int nreaches,
    const struct T_OPERATIONAL *oper_ptr,
    const struct T_STREAM *stream_ptr,
    const struct T_INITIAL *initial_ptr,
    const struct T_COEFFICIENTS *coeff_ptr,
    double *DO_ptr,

```

```

    double *CBOD_ptr,
    double *NBOD_ptr)
{

    /* define internal variables */
    int count;                                /* step counter for reach */
    int counter;                              /* total step counter */
    int reach;                                /* reach counter */
    double x;                                 /* distant along current reach */
    double t;                                 /* pseudo-time */
    struct T_INITIAL initial_conditions;      /* initial conditions for reach */
    double cum_flow;                          /* cumulative flow */

    /* define function return values */
    double MIX_IT();
    double DO_EQUATION();
    double CBOD_EQUATION();
    double NBOD_EQUATION();

    /* loop over number of reaches */
    for (reach = 0, counter = 0; reach < nreaches; reach++) {

        /* define initial conditions for reach */
        if (reach == 0) {

            /* first reach is equal to its own initial conditions */
            initial_conditions = *initial_ptr;

            /* initialize the cumulative flow */
            cum_flow = stream_ptr->flow;

        } else {

            /* mix DO streams */
            initial_conditions.DO = MIX_IT(cum_flow,
                stream_ptr->flow,
                *(DO_ptr - 1),
                initial_ptr->DO);

            /* mix CBOD streams */
            initial_conditions.CBOD = MIX_IT(cum_flow,
                stream_ptr->flow,
                *(CBOD_ptr - 1),
                initial_ptr->CBOD);

            /* mix NBOD streams */
            initial_conditions.NBOD = MIX_IT(cum_flow,
                stream_ptr->flow,
                *(NBOD_ptr - 1),
                initial_ptr->NBOD);

            /* update cumulative flow for next reach */
            cum_flow += stream_ptr->flow;

        }; /* end if */

        /* loop over number of steps and save results */
        for (count = 0; count < oper_ptr->nsteps; count++, counter++) {

```

```

    /* define distance */
    x = count*(oper_ptr->dx);

    /* calculate pseudo-time and convert to days */
    t = x/((stream_ptr->velocity)*3600.0*24.0);

    /* calculate dissolved oxygen */
    *DO_ptr = DO_EQUATION(t,
        initial_conditions,
        *coeff_ptr);

    /* calculate CBOD */
    *CBOD_ptr = CBOD_EQUATION(t,
        initial_conditions,
        *coeff_ptr);

    /* calculate NBOD */
    *NBOD_ptr = NBOD_EQUATION(t,
        initial_conditions,
        *coeff_ptr);

    /* increment step array pointers */
    DO_ptr++;
    CBOD_ptr++;
    NBOD_ptr++;

}; /* end step for */

/* increment reach array pointers */
stream_ptr++;
coeff_ptr++;
initial_ptr++;
oper_ptr++;

}; /* end reach for */

/* write status */
puts("Dissolved Oxygen profile calculated");

} /* end CALC_DO_PROFILE */

/*****
/* MIX_IT: This function mixes two flow streams.          */
*****/

double MIX_IT(
    double flow1,      /* flow rate for stream 1 */
    double flow2,      /* flow rate for stream 2 */
    double component1, /* address of mixing component for stream 1 */
    double component2) /* mixing component for stream 2 */
{
    return (component1*flow1 + component2*flow2)/(flow1 + flow2);
} /* end MIX_IT */

```

```

/*****
/* WRITE_DO_PROFILE: This subroutine writes out the plot file.      */
/*****

void WRITE_DO_PROFILE(
    char output_file[50],          /* output file */
    int nreaches,                 /* number of reaches */
    const struct T_OPERATIONAL *oper_ptr, /* operational data */
    const double *DO_ptr,         /* DO output array */
    const double *CBOD_ptr,       /* CBOD array */
    const double *NBOD_ptr,       /* NBOD array */
    const double *SP_ptr)         /* Streeter-Phelps */
{
    /* define file pointer */
    FILE *outfile;

    /* define internal variables */
    int count;          /* reach nstep count */
    int counter;        /* total step counter */
    int reach;          /* current reach */
    double x;           /* distance along stream */

    /* open output file */
    if ((outfile = fopen(output_file,"w")) == NULL ) {
        puts ("ERROR: Cannot open output file \n");
        exit (1);
    }; /* end if */

    /* initialize distance */
    x = 0.0;

    /* print header to file */
    fprintf(outfile,"Reach, Distance (ft), Distance (miles),"
        " Total DO Deficit, Carbonaceous BOD, Nitrogenous BOD,"
        " Streeter-Phelps DO Deficit\n");

    /* loop over the number of reaches */
    for (reach = 0, counter = 0; reach < nreaches; reach++) {

        /* loop over number of steps and save results */
        for (count = 0; count < oper_ptr->nsteps; count++, counter++) {

            /* increment x */
            x += oper_ptr->dx;

            fprintf(outfile,
                "%2d, %10.11f, %10.51f, %12.51f, %12.51f, %12.51f, %12.51f\n",
                reach,
                x,
                x/5280.0,
                *DO_ptr,
                *CBOD_ptr,
                *NBOD_ptr,
                *SP_ptr);

            /* increment step array pointers */
            DO_ptr++;
            CBOD_ptr++;
            NBOD_ptr++;
            SP_ptr++;
        }
    }
}

```

```
}; /* end step for */

/* increment reach array pointers */
oper_ptr++;

}; /* end reach for */

/* close file */
close (outfile);

/* write status */
puts("DO profiles written successfully");
puts(" ");
puts(" ");

} /* end WRITE_DO_PROFILE */
```

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APPENDIX B
BASELINE INPUT FILES
FOR THE SENSITIVITY ANALYSES
AND CASE STUDIES

TITLE: Baseline file for sensitivity analyses

**** Constant Values ****

1	nreaches	number of reaches
20.0	Temperature	Water temperature [10-30 deg C]
30.0	P	Phytoplankton chlorophyl [5-500 micro-g/L]
300.0	Is	Solar rad. at max phy. growth [250-500 ly/day]
0.50	f	Photoperiod [day]
0.2	aop	DO/chlorophyl alpha ratio [0.1-0.3 (mg DO)/(micro-g chl a)]
1.8	Gmax	Max. phyto. growth rate [1.5-3.0 1/d]

**** REACH 0 ****

1000000.0	Length	Length of reach [ft]
1.0	Velocity	Flow velocity [ft/s]
5.0	Depth	Average stream depth [ft]
1000.0	Flow	Flow rate [ft^3/s]
-1.0	Ka	Reaeration coefficient [1/d]
-1.0	Kd	Effective deoxygenation rate [1/d]
-1.0	Kr	Overall loss rate [1/d]
-1.0	Kn	Nitrification rate [1/d]
-1.0	Pa	Average gross DO prod. [mg DO/(L day)]
-1.0	R	Respiration rate [mg DO/(L day)]
-1.0	Sb	Sediment oxygen demand [mg DO/(L day)]
0.50	Areal_Sb	Areal averaged SOD rate [0.05-5.0 g DO/(L day)]
1.00	Ke	Light extinction coefficient [0.1-5.0/m]
750.0	Ia	Avg. daily solar rad. [500-1000 ly/day]
100	nsteps	Numer of steps to loop over
0.0	initial DO	Initial DO Deficit [mg/L]
20.0	initial CBOD	Initial CBOD concentration [mg/L]
10.0	initial NBOD	Initial NBOD concentration [mg/L]

Title: Baseline input file for the one-point-source case studies

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**** Constants ****
2          nreaches          number of reaches
20.0       Temperature       Water temperature [10-30 deg C]
30.0       P                 Phytoplankton chlorophyl [5-500 micro-g/L]
300.0      Is                Solar rad. at max phy. growth [250-500 ly/day]
0.50      f                 Photoperiod [day]
0.2       aop                DO/chlorophyl alpha ratio [0.1-0.3 (mg DO)/(micro-g chl
a)]
1.8       Gmax               Max. phyto. growth rate [1.5-3.0 1/d]

**** REACH 0 ****
100.0     Length            Length of reach [ft]
0.5       Velocity          Flow velocity [ft/s]
2.0       Depth             Average stream depth [ft]
20.0      Flow              Flow rate [ft^3/s]
-1.0      Ka                Reaeration coefficient [1/d]
-1.0      Kd                Effective deoxygenation rate [1/d]
-1.0      Kr                Overall loss rate [1/d]
-1.0      Kn                Nitrification rate [1/d]
-1.0      Pa                Average gross DO prod. [mg DO/(L day)]
-1.0      R                 Respiration rate [mg DO/(L day)]
-1.0      Sb                Sediment oxygen demand [mg DO/(L day)]
0.50      Areal_Sb          Areal averaged SOD rate [0.05-5.0 g DO/(L day)]
1.00      Ke                Light extinction coefficient [0.1-5.0/m]
750.0     Ia                Avg. daily solar rad. [500-1000 ly/day]
1         nsteps            Numer of steps to loop over
0.0       initial DO        Initial DO Deficit [mg/L]
0.0       initial CBOD      Initial CBOD concentration [mg/L]
0.0       initial NBOD      Initial NBOD concentration [mg/L]

**** REACH 1 ****
52800.0   Length            Length of reach [ft]
0.5       Velocity          Flow velocity [ft/s]
2.0       Depth             Average stream depth [ft]
6.0       Flow              Flow rate [ft^3/s]
-1.0      Ka                Reaeration coefficient [1/d]
-1.0      Kd                Effective deoxygenation rate [1/d]
-1.0      Kr                Overall loss rate [1/d]
-1.0      Kn                Nitrification rate [1/d]
-1.0      Pa                Average gross DO prod. [mg DO/(L day)]
-1.0      R                 Respiration rate [mg DO/(L day)]
-1.0      Sb                Sediment oxygen demand [mg DO/(L day)]
0.50      Areal_Sb          Areal averaged SOD rate [0.05-5.0 g DO/(L day)]
1.00      Ke                Light extinction coefficient [0.1-5.0/m]
750.0     Ia                Avg. daily solar rad. [500-1000 ly/day]
500       nsteps            Numer of steps to loop over
0.0       initial DO        Initial DO Deficit [mg/L]
40.0      initial CBOD      Initial CBOD concentration [mg/L]
10.0      initial NBOD      Initial NBOD concentration [mg/L]

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Title: Baseline input file for the two-point-source case studies

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**** Constants ****
3          nreaches          number of reaches
20.0      Temperature       Water temperature [10-30 deg C]
30.0      P                  Phytoplankton chlorophyl [5-500 micro-g/L]
300.0     Is                 Solar rad. at max phy. growth [250-500 ly/day]
0.50     f                   Photoperiod [day]
0.2      aop                 DO/chlorophyl alpha ratio [0.1-0.3 (mg DO)/(micro-g chl
a)]
1.8      Gmax                Max. phyto. growth rate [1.5-3.0 1/d]

**** REACH 0 ****
100.0     Length            Length of reach [ft]
0.5       Velocity          Flow velocity [ft/s]
2.0       Depth             Average stream depth [ft]
20.0      Flow              Flow rate [ft^3/s]
-1.0     Ka                 Reaeration coefficient [1/d]
-1.0     Kd                 Effective deoxygenation rate [1/d]
-1.0     Kr                 Overall loss rate [1/d]
-1.0     Kn                 Nitrification rate [1/d]
-1.0     Pa                 Average gross DO prod. [mg DO/(L day)]
-1.0     R                  Respiration rate [mg DO/(L day)]
-1.0     Sb                 Sediment oxygen demand [mg DO/(L day)]
0.50     Areal_Sb           Areal averaged SOD rate [0.05-5.0 g DO/(L day)]
1.00     Ke                 Light extinction coefficient [0.1-5.0/m]
750.0    Ia                 Avg. daily solar rad. [500-1000 ly/day]
1         nsteps            Numer of steps to loop over
0.0      initial DO         Initial DO Deficit [mg/L]
0.0      initial CBOD       Initial CBOD concentration [mg/L]
0.0      initial NBOD       Initial NBOD concentration [mg/L]

**** REACH 1 ****
52800.0   Length            Length of reach [ft]
0.5       Velocity          Flow velocity [ft/s]
2.0       Depth             Average stream depth [ft]
6.0       Flow              Flow rate [ft^3/s]
-1.0     Ka                 Reaeration coefficient [1/d]
-1.0     Kd                 Effective deoxygenation rate [1/d]
-1.0     Kr                 Overall loss rate [1/d]
-1.0     Kn                 Nitrification rate [1/d]
-1.0     Pa                 Average gross DO prod. [mg DO/(L day)]
-1.0     R                  Respiration rate [mg DO/(L day)]
-1.0     Sb                 Sediment oxygen demand [mg DO/(L day)]
0.50     Areal_Sb           Areal averaged SOD rate [0.05-5.0 g DO/(L day)]
1.00     Ke                 Light extinction coefficient [0.1-5.0/m]
750.0    Ia                 Avg. daily solar rad. [500-1000 ly/day]
500      nsteps            Numer of steps to loop over
0.0      initial DO         Initial DO Deficit [mg/L]
40.0     initial CBOD       Initial CBOD concentration [mg/L]
10.0     initial NBOD       Initial NBOD concentration [mg/L]

**** REACH 2 ****
52800.0   Length            Length of reach [ft]
0.5       Velocity          Flow velocity [ft/s]
2.0       Depth             Average stream depth [ft]
6.0       Flow              Flow rate [ft^3/s]
-1.0     Ka                 Reaeration coefficient [1/d]
-1.0     Kd                 Effective deoxygenation rate [1/d]
-1.0     Kr                 Overall loss rate [1/d]
-1.0     Kn                 Nitrification rate [1/d]
-1.0     Pa                 Average gross DO prod. [mg DO/(L day)]
-1.0     R                  Respiration rate [mg DO/(L day)]

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-1.0	Sb	Sediment oxygen demand [mg DO/(L day)]
0.50	Areal_Sb	Areal averaged SOD rate [0.05-5.0 g DO/(L day)]
1.00	Ke	Light extinction coefficient [0.1-5.0/m]
750.0	Ia	Avg. daily solar rad. [500-1000 ly/day]
500	nsteps	Numer of steps to loop over
0.0	initial DO	Initial DO Deficit [mg/L]
40.0	initial CBOD	Initial CBOD concentration [mg/L]
10.0	initial NBOD	Initial NBOD concentration [mg/L]