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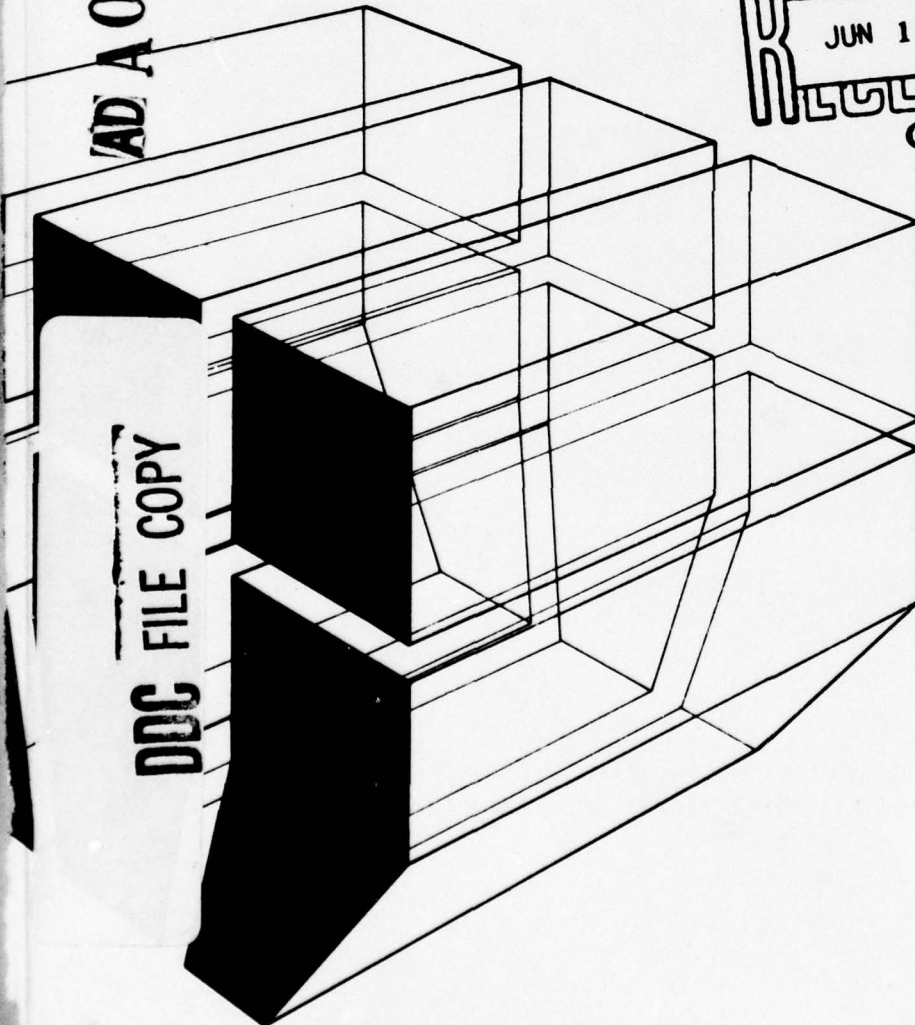
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BASIC ANALYTICAL MODEL FOR ENVIRONMENTAL  
IMPACT ASSESSMENT OF SURFACE WATER  
RESOURCES—DOSAG USER MANUAL

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by  
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*James E. Hays*  
JAMES E. HAYS  
Colonel, Corps of Engineers  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report discusses and provides user instructions for a computerized water quality model that will help satisfy the Army environmental planner's need for quantitative information on dissolved oxygen resources in a stream caused by new Army projects or activities. The information provided by output from this model will be useful for providing data for impacts on the dissolved oxygen content of a stream for a single-reach, single-point-source pollutant inflow situation with steady-flow conditions. Three subprograms within the model are used to calculate the impact of carbonaceous and nitrogenous waste discharges on the oxygen resources in a receiving water body, the ultimate biological oxygen			

*Jim*

cont

Block 20 continued.

→ demand and deoxygenation coefficients for both carbonaceous and nitrogenous waste discharges, and annual variations in temperature of a water body.

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## FOREWORD

This project was performed by the U.S. Army Construction Engineering Research Laboratory (CERL), Environmental Division (EN), for the Directorate of Military Programs under Project 4A762720A896, "Environmental Quality for Construction and Operation of Military Facilities"; Task 01, "Environmental Quality Management for Military Facilities"; Work Unit 006, "Analytical Model System for Prediction of Environmental Impacts." Dr. L. Schindler was the OCE Technical Monitor.

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# BASIC ANALYTICAL MODEL FOR ENVIRONMENTAL IMPACT ASSESSMENT OF SURFACE WATER RESOURCES--DOSAG USER MANUAL

## 1 INTRODUCTION

### Background

The Environmental Impact Computer System (EICS),<sup>1\*</sup> developed by the U.S. Army Construction Engineering Research Laboratory (CERL) provides systematic procedures and a technical data base to help Army planners and decision-makers perform environmental analysis and prepare and review environmental impact assessments and statements (EIAs/EISs). EICS provides qualitative information but does not provide the tools needed to quantify environmental impacts. The Council on Environmental Quality requires quantification whenever possible for EIAs/EISs.

The computerized model discussed in this report was developed to help fulfill the need for quantitative water quality analysis during environmental impact analysis. It will be used primarily by Army planners and decision-makers associated with Facility Engineering to obtain information for environmental analysis preparatory to writing an EIA/EIS.

### Objective

The objective of this study was to develop and provide user instructions for a computerized basic water quality model which could be used to quantify impacts on the dissolved oxygen content of a stream resulting from Army activities. This model can be used for a single-reach,\*\* single-point-source pollutant inflow with steady-flow conditions.

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<sup>1</sup>L. V. Urban, et al., *Computer-Aided Environmental Impact Analysis for Construction Activities--User Manual*, Technical Report E-50/ADA008988 (U.S. Army Construction Engineering Research Laboratory, March 1975).

\*EICS helps Army planners efficiently identify primary and secondary impacts of proposed Army projects or activities and suggests ways to mitigate these impacts. EICS is part of the Environmental Technical Information System, which includes two other operating systems: the Economic Impact Forecast System and the Computer-Aided Environmental Legislative Data System.

\*\*Section of a stream unaffected by water withdrawals (water treatment plant), discharges (waste treatment plant effluents, tributaries), or other physical modifications like dams, weirs, locks, etc.

### Approach

Three analysis techniques are combined into a single model capable of quantifying impacts relating to DO, and related parameters of BOD and water temperature. Fourier series analysis is used with historical water temperature data to develop an annual water temperature profile. Five-day BOD data are used to calculate the ultimate BOD and deoxygenation rate coefficients for both carbonaceous and nitrogenous waste discharges for receiving water. The effects of reaeration and photosynthesis are analyzed in the computations.

### Model Requirements

Several factors were considered when selecting techniques for predicting the effect of waste effluents on the dissolved oxygen (DO) content of streams. The modeling of DO in streams is a well-developed science, and several models can be used for this purpose. DOSAG-I and QUAL I are examples of well-documented models which have been proven through widespread application;<sup>2</sup> however, these models are more complex than appears to be necessary. Two or three weeks of data acquisition and preparation are often needed to use these types of models. Clearly, Army installation personnel would have difficulty conducting such analysis on a routine basis.

A variety of situations can result in stream BOD loading. The most familiar is point source effluent from wastewater treatment plants. Area source pollution has received great interest recently; however, this type of analysis is also very complex. For impact analysis, techniques which consider the primary DO sources (reaeration and photosynthesis) and the primary DO sinks (carbonaceous and nitrogenous biochemical oxygen demand [BOD]) are adequate. The usual situations for which these techniques will be used and the capabilities of the typical user suggest that a single-reach, steady-flow, point source model is appropriate.† The techniques provide rapid analysis for users having little expertise in water-quality modeling and require a minimum of input data. The most common use of these techniques is expected to be prediction of impacts from various levels of wastewater treatment plant operating efficiency. The worst-case situation is expected to occur during low-flow, high-temperature stream conditions.

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<sup>2</sup>*Simulation of Water Quality in Streams and Canals, Program Documentation and User Manual* (Texas Water Development Board, September 1970).

†Verification of this approach is under way. Techniques to expand the model to include additional tributaries and effluent sources are being investigated.

### Mode of Technology Transfer

User-related information from this report will be issued as an Engineering Technical Letter. The computer program will be documented in another report, and the source deck will be available from National Technical Information Service. The computer program will remain operative on the time-sharing computer system (Naval Shipyard Research and Development Center) which would allow access by field users.

After the decision is made concerning where the Environmental Technical Information System (ETIS) will be field-implemented, the model will be integrated and appropriately referenced in the ETIS.

## 2 ANALYSIS FUNCTIONS

DOSAG, the computer program for this model, is a collection of subroutines which perform basic water quality analysis functions, and is used to quantify impacts on BOD and DO. DOSAG has been developed to evaluate:

1. Annual variations in a water body temperature through Fourier Series analysis, using historical data
2. The ultimate BODs and deoxygenation rate coefficients for both carbonaceous and nitrogenous waste discharges
3. The impact of carbonaceous and nitrogenous waste discharges on the DO of a receiving water body. The program has several options for reaeration or photosynthesis.

### Temperature

Temperature is probably one of the most significant and widely measured parameters among the water quality characteristics of surface waters. Most of the physical, chemical, and biological properties of water are functions of temperature. As temperature increases, the saturation concentration of DO decreases and the atmospheric reaeration rate increases. An increase in water temperature has both beneficial and deleterious effects on the environment. Studies have indicated that for each 10°F increase in temperature,<sup>3</sup> the cost of chemicals to coagulate and treat water effectively can

<sup>3</sup>G. E. Arnold, "Thermal Pollution of Surface Supplies," *Journal American Water Works Association*, 54:1332 (November 1962).

be reduced by \$0.30 to \$0.50 per million gallons. The effectiveness of chlorination and the efficiency of sedimentation tanks and filtration units are enhanced by higher temperatures. On the other hand, high temperatures increase metabolic rates of organisms, which increases the demand for DO. Higher temperatures may also promote algae growth if other conditions are favorable.

Traditionally, analytical models for water temperatures have been based on two different precepts. The first is the heat budget of a body of water, which considers factors like incident solar radiation, atmospheric radiation, intensity of reflected solar radiation, back radiation or radiation emitted from the surface of the water body, conducted heat, loss of heat due to evaporation, and convection of heat with evaporated water, etc. This method requires extensive instrumentation to evaluate various factors affecting the heat budget and is prohibitively expensive and time-consuming.

The second approach is to develop an analytical model for water temperature based on historical water temperature data for any stream or lake. The existence of cyclic variations in mean daily, weekly, or monthly water temperatures was reported by Kothandaraman and Evans,<sup>4</sup> Thomann,<sup>5</sup> and Ward.<sup>6</sup> These investigators indicated that the harmonic function with a periodicity of 1 year fits water temperature data in lakes, estuaries, and rivers, and accounts for approximately 95 percent of the total variance.

The annual temperature variations have been found to fit an empirical equation of the form:

$$T = p \sin bx + q \cos bx + \bar{T} \quad [\text{Eq 1}]$$

where T is the calculated water temperature (°C), x is the number of days since January 1 (x = 1 for January 1), p and q are the components of the harmonic, b is a constant given as

<sup>4</sup>V. Kothandaraman and R. L. Evans, "Annual Temperature Variations in an Impoundment in Central Illinois," *Journal American Water Works Association*, 62:639 (October 1970).

<sup>5</sup>R. V. Thomann, "Time Series Analysis of Water Quality Data," *Journal of the Sanitary Engineering Division*, 93:1 (American Society of Civil Engineers [ASCE], February 1967).

<sup>6</sup>J. C. Ward, "Annual Variation of Stream Water Temperature," *Journal of the Sanitary Engineering Division*, 89:1 (ASCE, December 1963).

$$b = \frac{360}{365} \text{ days} = 0.987 \text{ degrees per day or } 0.0172 \text{ radians per day} \quad [\text{Eq 2}]$$

and  $\bar{T}$  is the mean annual temperature of the observed record.

The standard deviation,  $\sigma$ , for a set of observations is given by the following equation:

$$\sigma = \sqrt{\frac{\sum(T_i - \bar{T})^2}{N-1}} \quad [\text{Eq 3}]$$

The standard error of estimate,  $S_y$ , is given by

$$S_y = \sqrt{\frac{\sum(T_i - T)^2}{N}} \quad [\text{Eq 4}]$$

and the correlation coefficient,  $r$ , is given by

$$r = \sqrt{1 - \frac{S_y^2}{\sigma^2}} \quad [\text{Eq 5}]$$

where  $T_i$  is the observed temperature and  $N$  is the total number of observations.  $N$  pairs of evenly spaced values of  $x$  and  $T_i$  covering the entire period of 1 year of multiples thereof are required to use these algorithms. Figure 1 shows various entities of this temperature model.

The parameters  $p$  and  $q$  of Eq 1 are determined so that the sum of the squares of the residual errors,  $R^2$ , i.e., the sum of the squares of the differences between the predicted and observed temperatures, is a minimum. This is expressed mathematically as

$$\sum R^2 = \sum [p \sin bx + q \cos bx + \bar{T} - T_i]^2 \quad [\text{Eq 6}]$$

This condition is satisfied if the first partial derivatives of  $R$  with respect to  $p$  and  $q$  are zero.

$$\frac{\partial(\sum R^2)}{\partial p} = 2\sum(p \sin bx + q \cos bx + \bar{T} - T_i) \sin bx = 0 \quad [\text{Eq 7}]$$

$$\frac{\partial(\sum R^2)}{\partial q} = 2\sum(p \sin bx + q \cos bx + \bar{T} - T_i) \cos bx = 0 \quad [\text{Eq 8}]$$

Eqs 7 and 8 can be rearranged to give the two normal equations for evaluating  $p$  and  $q$  as follows:

$$p \sum \sin^2 bx + q \sum \sin bx \cos bx + \bar{T} \sum \sin bx - \sum T_i \sin bx = 0 \quad [\text{Eq 9}]$$

$$p \sum \sin bx \cos bx + q \sum \cos^2 bx + \bar{T} \sum \cos bx - \sum T_i \cos bx = 0 \quad [\text{Eq 10}]$$

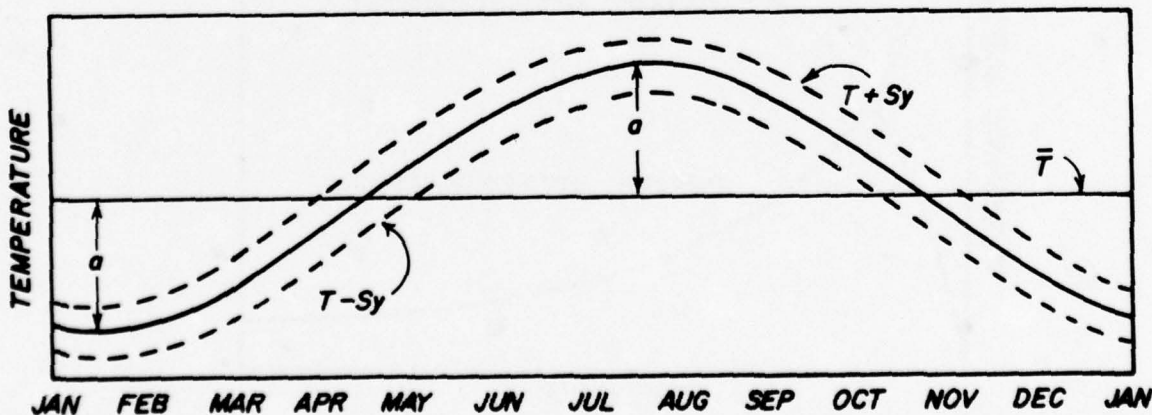


Figure 1. Annual variations in water temperatures.

Solving these two equations for p and q provides

$$q = \frac{[(\Sigma \sin bx \cos bx)(\Sigma T_i \sin bx - \bar{T} \Sigma \sin bx) - \Sigma \sin^2 bx (\Sigma T_i \cos bx - \bar{T} \Sigma \cos bx)]}{(\Sigma \sin bx \cos bx)^2 - (\Sigma \sin^2 bx)(\Sigma \cos^2 bx)}$$

[Eq 11]

and

$$p = \frac{(\Sigma T_i \sin bx - \bar{T} \Sigma \sin bx) \Sigma \cos^2 bx - (\Sigma T_i \cos bx - \bar{T} \Sigma \cos bx) \Sigma \sin bx \cos bx}{\Sigma \sin^2 bx \Sigma \cos^2 bx - (\Sigma \sin bx \cos bx)^2}$$

[Eq 12]

### Biochemical Oxygen Demand

The wastes discharged into a stream from municipal and industrial plants contain a variety of chemical compounds. Of primary interest is that portion of the waste which is biodegradable, and hence oxygen-consuming. When this material is introduced into a water course, it undergoes biochemical oxidation when micro-organisms use the organic matter for energy and growth.

If enough DO is present in the water, the microflora will be primarily aerobic, using the DO to carry out oxidation reactions, and producing water and carbon dioxide as end products. However, if enough oxygen is not present, anaerobic organisms predominate, provid-

ing undesirable end products. In addition, the concentration levels of oxygen have profound effects on the physiology and type of fish found in the water bodies. The lethal effect of low concentrations of DO appears to be increased by the presence of toxic substances, such as excessive dissolved carbon dioxide, ammonia, lead, copper, etc.

Because of the variety of oxygen-demanding organics in the waste, it is common to measure the strength of wastes in terms of BOD rather than to analyze the chemical constituents of the wastes. Since the BOD reaction is closely related to the unimolecular type of reaction, a plot of the amount of the organic matter remaining versus time yields a parabolic curve similar to the decay curve for a radioactive element (see Figure 2). Likewise, a plot showing the amount of organic matter oxidized versus time produces a parabolic curve that is the reciprocal of the first.

Since the amount of oxygen used is directly proportional to the amount of organic matter oxidized in biochemical oxidations, a plot of oxygen used versus time would produce a parabolic-type curve like the one produced for organic matter oxidized (Figure 2).

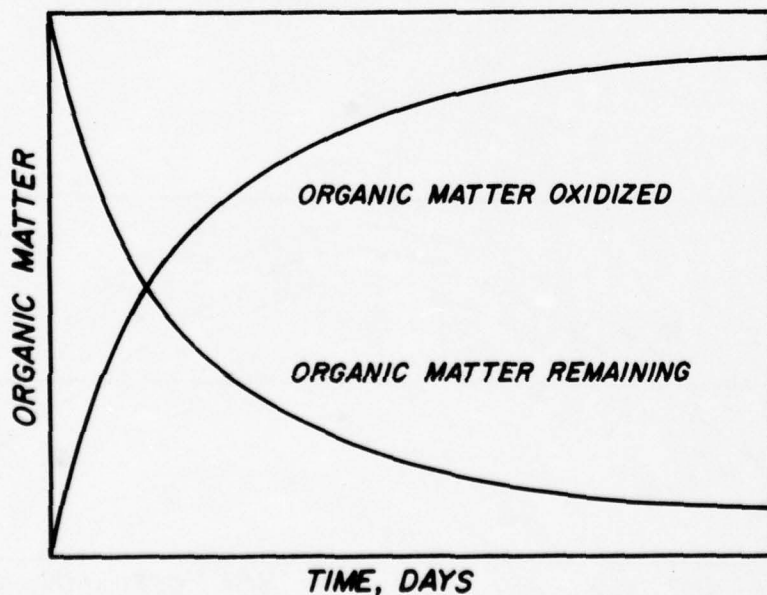


Figure 2. Plots of oxygen used and organic matter oxidized.

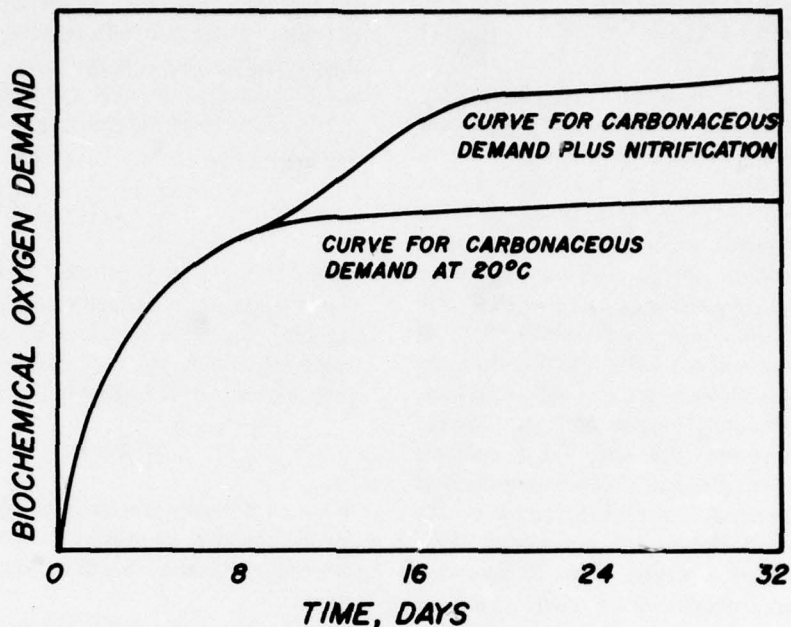


Figure 3. Typical BOD curve.

Figure 3 is a typical BOD curve for a municipal effluent. For the first 8 to 10 days, its characteristics are similar to those of the curve for organic matter oxidized (Figure 2). After that time, the BOD curve digresses radically from the course it would be expected to follow as a monomolecular or first-order reaction. This is because the nitrifying bacterial population has become large enough to significantly increase the oxygen demand exerted by those bacteria. These organisms oxidize nitrogen (in the form of ammonia) to nitrite and nitrate.

On the basis of first-order kinetics, the rate of BOD removal in a water body is given by

$$\frac{dL}{dt} = -K_c L_c - K_n L_n \quad [\text{Eq 13}]$$

where

$L$  = total BOD remaining at any time,  $t$ , mg/l  
 $L_c$  = carbonaceous BOD remaining at any time,  $t$ , mg/l

$L_n$  = nitrogenous BOD remaining at any time,  $t$ , mg/l

$K_c$  = carbonaceous deoxygenation coefficient to the base  $e$ , per day

$K_n$  = nitrogenous deoxygenation coefficient to the base  $e$ , per day

Integration of the carbonaceous term of this equation yields:

$$L_c = L_{uc} e^{-K_c t} \quad [\text{Eq 14}]$$

where

$L_{uc}$  is the ultimate carbonaceous demand. Integration of the nitrogenous term of Eq 13 yields:

$$L_n = L_{un} e^{-K_n t} \quad [\text{Eq 15}]$$

where  $L_{un}$  is the ultimate nitrogenous demand.

If  $L = L_c + L_n$ , then

$$L = L_{uc} e^{-K_c t} + L_{un} e^{-K_n t} \quad [\text{Eq 16}]$$

If there is a time lag,  $t_0$ , for the onset of nitrogenous demand from the carbonaceous demand, which invariably is the case, then Eq 16 takes the form

$$L = L_{uc} e^{-K_c t} + L_{un} e^{-K_n(t-t_0)} \quad [\text{Eq 17}]$$

In the above equation, the factors  $L_{uc}$ ,  $L_{un}$ ,  $K_c$ , and  $K_n$  must be determined from the BOD time progression curve obtained under standardized laboratory conditions. To differentiate between the carbonaceous oxygen demand and the nitrogenous oxygen demand, the laboratory conducts tests on waste stream samples both with and without adding inhibitory agents to suppress the activity of nitrifying bacteria. BOD progression curves obtained from the samples without an inhibitor yield the combined BOD resulting from the oxidation of carbonaceous matter and ammonia. Results from samples containing an inhibitor yield the BOD values resulting from the oxidation of carbonaceous matter alone. The difference in the values obtained under these two conditions yields information on the BOD resulting from nitrification. Various chemicals have been tried as inhibitors; methylene blue, allylthiourea, and acidification are among the most widely used.

Ultimate oxygen demands and deoxygenation coefficients are estimated from the BOD progression data by means of analytical procedures. The Thomas slope method, the method of moments, the rapid ratio, the daily difference method, the Reed-Theriault method, and the least squares method of nonlinear curve fitting have all been used to estimate ultimate BOD and the deoxygenation coefficients. Each method gives a slightly different set of values for these two parameters. The Reed-Theriault method, which provides reliable information of ultimate BOD and deoxygenation rate consistent with the effort involved, is explained in the following paragraphs.

The Reed-Theriault method<sup>7</sup> estimates the ultimate BOD and deoxygenation coefficient from the observed BOD progression, using the least squares principle to minimize the residual errors between the observed data and the fitted monomolecular curve. To apply the procedure, a method of successive approximations involving trial and error is used in which it is necessary to assume a trial value of  $K$ . (Note: The subscripts of  $c$  and  $n$  for  $K$  used earlier have been dropped here. The procedure

is applicable equally to data for both carbonaceous demand and for nitrogenous demand.) This procedure is then used together with the observed data to determine a correction factor to the assumed  $K$  value. The operation is repeated with the corrected  $K$  value until the correction factor is small, i.e., until the assumed and calculated values of  $K$  approach one another. The details of the Reed-Theriault algorithm are given in Eqs 18 through 26.

$$Y = L_u(1 - e^{-Kt}) \quad [\text{Eq 18}]$$

where  $Y$  is the BOD satisfied in time,  $t$ , and all the other terms are as defined earlier. For the purpose of reducing this expression to a linear form, an approximate value of  $K$  has been assigned so that the most probable value of  $K$  is given by the relation

$$K = K^1 + h \quad [\text{Eq 19}]$$

in which  $K^1$  is the trial value, and  $h$  is a relatively small number, positive or negative, whose magnitude is to be determined. Substituting this value into Eq 18,

$$\begin{aligned} Y &= L_u [1 - e^{-(K^1+h)t}] \\ &= L_u(1 - e^{-K^1 t}) + L_u h t e^{-K^1 t} \end{aligned} \quad [\text{Eq 20}]$$

This is of the form

$$Y = a f_1 + b f_2 \quad [\text{Eq 21}]$$

in which  $a = L_u$ ,  $b = L_u h$ ,  $f_1 = 1 - e^{-K^1 t}$ , and  $f_2 = t e^{-K^1 t}$ . For Eq 21, the difference between an observed and a calculated quantity is  $Y - a f_1 - b f_2$ . The sum,  $R$ , of the squares of the residual errors is

$$R = \sum (Y - a f_1 - b f_2)^2 \quad [\text{Eq 22}]$$

The most probable values of the constants  $a$  and  $b$  will be obtained when  $R$  is a minimum. Equations defining this condition are:

$$\frac{\partial R}{\partial a} = \sum f_1 Y - a \sum f_1^2 - b \sum f_1 f_2 = 0 \quad [\text{Eq 23}]$$

$$\frac{\partial R}{\partial b} = \sum f_2 Y - a \sum f_1 f_2 - b \sum f_2^2 = 0 \quad [\text{Eq 24}]$$

The solutions of Eqs 23 and 24 are:

$$a = \frac{\sum f_2^2 \sum f_1 Y - \sum f_1 f_2 \sum f_2 Y}{\sum f_1^2 \sum f_2^2 - (\sum f_1 f_2)^2} \quad [\text{Eq 25}]$$

<sup>7</sup>Lowell J. Reed and Emery J. Theriault, "The Statistical Treatment of Reaction-Velocity Data II, Least Squares Treatment of the Unimolecular Expression:  $Y = L(1 - e^{-Kt})$ ," *Journal of Physical Chemistry*, Vol 35(4) (1931), pp 950-971.

and

$$b = \frac{\Sigma f_1^2 \Sigma f_2 Y - \Sigma f_1 f_2 \Sigma f_1 Y}{\Sigma f_1^2 \Sigma f_2^2 - (\Sigma f_1 f_2)^2} \quad [\text{Eq 26}]$$

From the values of a and b as obtained above,  $L_u$  and h can be calculated. If the value of h is greater than the tolerance value, suitable correction for the assumed K value (i.e.,  $K^1$ ) should be made, and the whole computation should be repeated. For stream sanitation work, a tolerance value of 0.01 for h is adequate.

The BODs exerted by waste samples are determined under standardized laboratory conditions at 20°C. Consequently, the values of ultimate BOD,  $K_c$ , and  $K_n$  obtained from the BOD progression data pertain to 20°C. To assess the impacts of waste discharges at temperatures other than 20°C, corrections for these values must be applied. The following equations are used for temperature correction purposes.

$$K_{c(T)} = K_{c(20)} \times 1.047^{(T-20)} \quad [\text{Eq 27}]$$

$$K_{n(T)} = K_{n(20)} \times 1.097^{(T-20)} \quad [\text{Eq 28}]$$

Range 10 to 22°C

$$K_{n(T)} = K_{n(20)} \times 1.203 \times 0.877^{(T-22)} \quad [\text{Eq 29}]$$

Range 22 to 30°C

$$L_{uc(T)} = L_{uc(20)} \times (0.02T + 0.6) \quad [\text{Eq 30}]$$

where T is the temperature in degrees Celsius of the waste stream under field conditions,  $K_{c(T)}$  is the value of the carbonaceous deoxygenation coefficient at T degrees Celsius,  $K_{c(20)}$  is the value at 20°C, and so on for the rest of the parameters defined earlier.

#### Reaeration and Photosynthesis

Many factors govern the DO content of rivers, streams, and other water bodies. Oxygen in the waters is consumed during the process of organic materials stabilization, oxidation of reduced compounds like ammonia, ferrous iron, and manganese compounds, and during aquatic plant respiration. Oxygen is replaced in natural water bodies largely through atmospheric reaeration and photosynthesis of aquatic plants. Evaluation of the river's DO content depends on the rates at which the processes listed above occur.

Even though atmospheric reaeration is the main source of oxygen replenishment in natural waters, the mechanism by which oxygen is absorbed is not well

understood. Various theories have been proposed to explain this mechanism. Some of these theories use parameters like surface film thickness, surface removal rate, etc.; however, these parameters are difficult to measure or to relate to common hydraulic variables. Therefore, many empirical and semi-empirical equations have been proposed to predict the reaeration rate. The following paragraphs briefly summarize some of these conceptual models and empirical equations.

Of the conceptual models, two film models by Lewis and Whitman, the penetration theory model by Higbie, the surface renewal theory model by Dankwerts, and the film penetration model by Dobbins are well known. All these models contain some intangible parameter which cannot be directly related to commonly measured hydraulic variables. While these models can be used to explain the reaeration process, they are not very useful for predicting the reaeration rates in streams. The following prediction equations can be applied more practically.

#### Prediction Equations

**O'Connor-Dobbins Equation.** O'Connor and Dobbins defined the rate of reaeration,  $K_2$  to the base, e, in terms of the rate of renewal of surface film, and assumed that the best estimate was given by the ratio of the vertical velocity fluctuation and mixing length. In streams in which there is pronounced velocity gradient, the following equation for nonisotropic turbulence was developed:

$$K_2 = 480D_m^{0.5}S^{0.25}H^{-1.25} \quad [\text{Eq 31}]$$

For isotropic turbulence in relatively deep channels where there is no pronounced velocity gradient,

$$K_2 = 127D_m^{0.5}S^{0.25}H^{-1.5} \quad [\text{Eq 32}]$$

where  $D_m$  is the coefficient of molecular dispersion, S is the channel slope, and H is the mean depth. Isotropic turbulence was assumed arbitrarily for Chezy coefficients greater than 17 and nonisotropic turbulence was assumed for coefficients less than 17. The authors subsequently concluded that the latter of the two equations is the more generally applicable and recommended that the first equation be ignored.<sup>8</sup>

<sup>8</sup>W. E. Dobbins, "1964 BOD and Oxygen Relationship in Streams," *Journal of the Sanitary Engineering Division*, Vol 90, No. SA3 (ASCE, 1964), pp 53-78.

**Churchill-Elmore-Buckingham Equation.** The empirical equation proposed by Churchill, et al., is based on regression analysis of the extensive field data from selected stream reaches within the Tennessee Valley Authority rivers. The data collected by these investigators rank as one of the best efforts in gathering field information on stream reaeration rates. The proposed empirical equation is

$$K_2 = 11.6V^{0.969}H^{-1.673} \quad [\text{Eq 33}]$$

in which  $K_2$  is the reaeration rate coefficient to the base,  $e$ ,  $\text{day}^{-1}$ ;  $V$  is the mean velocity of flow in feet/sec; and  $H$  is the mean depth of flow in feet. The equation was derived with a set of values for  $V$  and  $H$  ranging, respectively, from 1.85 to 5.00 ft/sec, and from 2.12 to 11.41 ft. Consequently, use of this equation is restricted to the values of mean velocity and mean depth that fall within these ranges.

**Isaacs and Gaudy Equation.** Isaacs and Gaudy measured reaeration in a circular flume in which the inner and outer walls could be driven at different speeds to simulate stream flow conditions. Multiple regression analysis on their data yielded the equation

$$K_2 = 7.05VH^{-3/2} \quad [\text{Eq 34}]$$

All the terms are as defined in the previous equation.

**Langbien and Durum Equation.** Langbien and Durum developed an empirical equation using all the published data on atmospheric reaeration. The proposed equation is

$$K_2 = 7.63VH^{-1.33} \quad [\text{Eq 35}]$$

All the terms are defined in the Churchill-Elmore-Buckingham equation.

Several other semi-empirical equations predict the reaeration rate coefficient  $K_2$ . Equations proposed by Krenkel and Orlob, Thackston and Krenkel, and others, involve determination of longitudinal dispersion in streams, which is expensive, both in terms of time and manpower. Prediction equations proposed by Churchill, et al., and by Langbien and Durum are reliable and acceptable for use.<sup>9</sup>

<sup>9</sup>R. E. Rathben, "Reaeration Coefficients of Streams—State of the Art," *J. Hydr. Div. Proc.*, Vol 103, No. 409 (ASCE, 1977).

#### Temperature Correction for Reaeration Coefficient

All the empirical equations given above are for determining the reaeration coefficient at 20°C. However, when the stream temperatures are other than 20°C, corrections must be applied. A widely accepted correction factor for the reaeration coefficient is

$$K_{2(T)} = K_{2(20)} \times 1.0241^{T-20} \quad [\text{Eq 36}]$$

where  $K_{2(T)}$  and  $K_{2(20)}$  are the values of reaeration coefficients at  $T^\circ\text{C}$  and  $20^\circ\text{C}$ , respectively.

The reaeration process due to absorption from the atmosphere is considered as a first-order reaction. The rate of oxygen absorption is dependent on the DO deficit,  $D$  in  $\text{mg}/\ell$  (which is defined as the difference between the DO saturation),  $C_s$  in  $\text{mg}/\ell$ , and the DO concentration  $C$  in  $\text{mg}/\ell$  at any time,  $t$ . The process can be expressed as

$$\frac{dc}{dt} = K_2(C_s - C) = K_2D = -\frac{dD}{dt} \quad [\text{Eq 37}]$$

If the initial DO concentration and deficit are defined as  $C_o$  and  $D_o$  at time  $t = 0$ , the solution to the differential Eq 37 is

$$C_s - C = (C_s - C_o)e^{-K_2t} \quad [\text{Eq 38}]$$

or

$$D = D_o e^{-K_2t} \quad [\text{Eq 39}]$$

Eqs 38 and 39 define the DO deficit with time when only the reaeration process is operative and no other process like deoxygenation, photosynthesis, respiration, etc., is affecting the system. In natural water bodies, all these processes interact, and therefore must be considered as coupled systems.

The solubility rate of oxygen in fresh water is dependent primarily on the water temperature. The saturation concentrations in water samples were adequately described<sup>10</sup> by the expression

$$C_s = 14.652 - 0.41022T + 0.007991T^2 - 0.000077774T^3 \quad [\text{Eq 40}]$$

<sup>10</sup>T. A. Butts and V. Kothandaraman, "Fitting First and Second Order BOD Reaction Equations to Stream Data," *Water and Sewage Works*, Vol 117 (1970), p 276.

where  $C_s$  is the saturation concentration in mg/l and  $T$  is the water temperature in degrees Celsius. Evaluation of the  $C_s$  term at any specific temperature is essential. Most of the models describing the DO/BOD relationships evaluate oxygen deficits. Thus, knowing the DO saturation concentrations and the DO deficits, expected DO concentrations could be determined by finding the difference between the  $C_s$  value and the DO deficit value.

Oxygen balance studies of polluted streams usually produce one or more dissolved oxygen profiles. Such a profile is referred to as a dissolved oxygen sag curve. The analysis of a stream's capacity to assimilate organic pollution has been based on the classical theory of Streeter and Phelps,<sup>11</sup> who considered only two mechanisms affecting DO budget in streams: (1) the biochemical oxidation of organic matter, and (2) the atmospheric reaeration of river water. Since their pioneering efforts several modifications have been proposed.<sup>12-14</sup>

The predictive equations developed in this report for BOD and DO profiles along a stream are based on the following assumptions:

1. Stream flow is steady and uniform.
2. BOD and DO are uniformly distributed over each cross section, so that the equation can be written in one-dimensional form.
3. The process for any river reach as a whole is a steady-state process, with the conditions at every cross section remaining unchanged over time.
4. Bacterial oxidation of carbonaceous and nitrogenous matter and the absorption of oxygen from the atmosphere are first-order reactions.

<sup>11</sup>H. W. Streeter and E. B. Phelps, "A Study of the Pollution and Natural Purification of the Ohio River," *Public Health Bulletin 146* (U.S. Public Health Service, 1925).

<sup>12</sup>T. R. Camp, *Water and Its Impurities* (Reinhold Publishing Corporation, 1963).

<sup>13</sup>W. E. Dobbins, "1964 BOD and Oxygen Relationship in Streams," *Journal of the Sanitary Engineering Division*, Vol 90, No. SA3 (ASCE, 1964), pp 53-78.

<sup>14</sup>D. J. O'Connor and W. E. Dobbins "Mechanisms of Reaeration in Natural Streams," *Trans. ASCE*, Vol 123 (ASCE, 1959).

5. The rate of BOD removal is proportional to the amount of BOD present, and the rate of reaeration is proportional to the oxygen deficit.

Factors affecting the DO/BOD relationship in streams considered in these equations are:

1. Oxygen demand by carbonaceous matter
2. Oxygen demand by nitrogenous matter
3. Oxygen addition due to atmospheric reaeration
4. Oxygen addition due to photosynthesis.

Other factors which could affect the oxygen balance, such as biological extraction of organic matter, benthic oxygen demand, and deposition or scouring of organic matter from the stream beds, are ignored as having a negligible effect. In considering the oxygen addition to streams because of photosynthesis, Camp<sup>15</sup> used a uniform net rate of oxygen addition, "a" mg/l/day, despite the fact that there is no oxygen addition from photosynthesis during periods of cloud cover or darkness. However, O'Connor<sup>16</sup> first introduced the concept that photosynthetic oxygen addition could be treated as a cyclic function with zero values during periods of darkness and as a specific functional value during daylight periods. Both concepts are discussed in the following two sections. Although the O'Connor and Dobbins method is believed to be more accurate, Camp's method requires less input data. It is left to the user to evaluate the importance of photosynthesis and to determine which method, if any, should be used. Figure 4 shows basic elements of dissolved oxygen balance models in streams.

#### Oxygen Balance Equations, Case 1

The rate of BOD removal in a stream on the basis of first-order reaction kinetics is given by

$$\frac{dL}{dt} = -K_c L_c - K_n L_n \quad [\text{Eq 41}]$$

where

$L$  = total BOD remaining at any time  $t$ , mg/l  
 $L_c$  = carbonaceous BOD remaining at any time  $t$ , mg/l

<sup>15</sup>T. R. Camp.

<sup>16</sup>O'Connor and Dobbins.

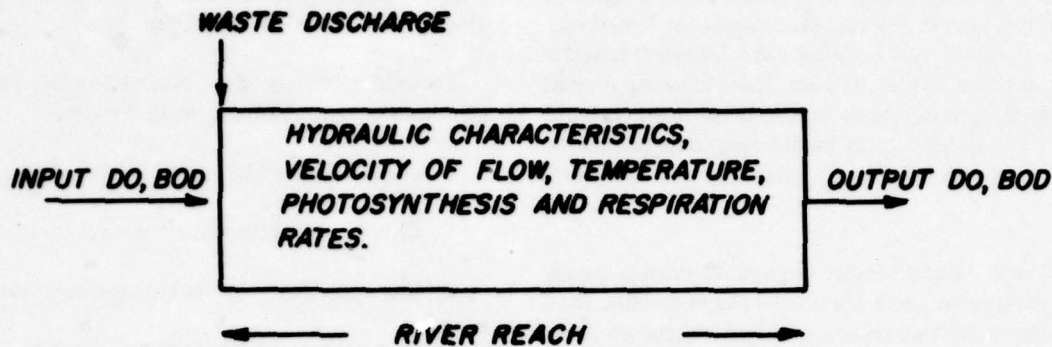


Figure 4. Basic model elements.

$L_n$  = nitrogenous BOD remaining at any time  $t$ , mg/l

$K_c$  = carbonaceous deoxygenation coefficient to the base  $e$ , per day

$K_n$  = nitrogenous deoxygenation coefficient to the base  $e$ , per day

Integration of Eq 41 with appropriate initial conditions yields

$$L = L_{uc}e^{-K_c t} + L_{un}e^{-K_n t} \quad [\text{Eq 42}]$$

where  $L_{uc}$  is the ultimate carbonaceous demand and  $L_{un}$  is the ultimate nitrogenous demand.

If there is a time lag ( $t_0$ ) for the onset of nitrogenous demand from the carbonaceous demand, which invariably is the case, then Eq 42 takes the form

$$L = L_{uc}e^{-K_c t} + L_{un}e^{-K_n(t-t_0)} \quad [\text{Eq 43}]$$

The reaction process in a stream due to atmospheric absorption is also a first-order reaction. The rate process is dependent on the DO deficit ( $D$  in mg/l) which is defined as the difference between the DO saturation concentration ( $C_s$  in mg/l) and the observed DO concentration ( $C$  in mg/l) in the stream. If oxygen addition from photosynthesis is considered to be at a uniform rate of " $a$ " mg/l/day,<sup>17</sup> then the rate of change of DO concentration resulting from only these two processes is given by

$$\frac{dC}{dt} = K_2(C_s - C) + a = K_2 D + a = -\frac{dD}{dt} \quad [\text{Eq 44}]$$

Since  $L$ , the BOD remaining to be satisfied, is measured in terms of oxygen consumed, and the rate of oxygen consumption equals the rate at which the BOD is satisfied, then

$$\frac{dD}{dt} = \frac{dL}{dt} \quad [\text{Eq 45}]$$

Combining the rates of these two reactions (Eqs 41 and 44) and writing the equation in terms of DO deficit yields the response of receiving waters to a single waste source. The differential equation is

$$\frac{dD}{dt} = K_c L_{uc}e^{-K_c t} + K_n L_{un}e^{-K_n(t-t_0)} - K_2 D - a \quad [\text{Eq 46}]$$

Solution to the differential Eq 46 is

$$De^{K_2 t} = \frac{K_c L_{uc}e^{(K_2 - K_c)t}}{K_2 - K_c} + \frac{K_n L_{un}}{K_2 - K_n} e^{K_2 t - K_n(t-t_0)} - \frac{ae^{K_2 t}}{K_2} + \text{constant} \quad [\text{Eq 47}]$$

When  $t = 0$  (i.e., at the time of initial observation,  $D = D_0$  [initial DO deficit]). This condition yields

$$\text{Constant} = D_0 - \frac{K_c L_{uc}}{K_2 - K_c} - \frac{K_n L_{un}}{K_2 - K_n} e^{K_n t_0} + \frac{a}{K_2}$$

<sup>17</sup>T. R. Camp, *Water and Its Impurities* (Reinhold Publishing Corporation, 1963).

Substituting this value of the constant in Eq 47,

$$D = \frac{K_c L_{uc}}{K_2 - K_c} (e^{-K_c t} - e^{-K_2 t}) + \frac{K_n L_{un}}{K_2 - K_n} [e^{-K_n(t-t_0)} - e^{-(K_2 t - K_n t_0)}] - \frac{a}{K_2} (1 - e^{-K_2 t}) + D_0 e^{-K_2 t} \quad [\text{Eq 48}]$$

Eq 48 gives a trace of the DO deficit along with stream stretch. Knowing the velocity of flow and the distance of the point of interest (i.e., the point at which DO concentration must be determined) from the initial point of reference, the elapsed time ( $t$  in days) can be evaluated. The DO deficit can be obtained from Eq 48, and the DO concentration at the desired river point can then be deduced.

Input for this analytical model is  $K_c$ ,  $L_{uc}$ ,  $K_2$ ,  $K_n$ ,  $L_{un}$ ,  $t_0$ ,  $a$ , and  $D_0$ . Methods for evaluating the parameters  $K_c$ ,  $L_{uc}$ ,  $K_n$ ,  $L_{un}$ ,  $K_2$ , and  $t_0$  have been discussed previously. Oxygen addition due to photosynthesis of aquatic plants ("a") must be determined in the field using the light and dark bottle technique.<sup>18</sup> Most frequently, the photosynthesis oxygen addition in flowing waters is insignificant and can be ignored in defining the oxygen balance equations. It is included in the model to cover those cases where photosynthesis is important.

#### Oxygen Balance Equations, Case 2 (O'Connor)

The drawback of the Camp approach is its failure to account for oxygen addition due to photosynthesis; realistically, a uniform rate covering the daylight and darkness periods is considered, even though no oxygen-producing photosynthesis occurs after sunset. This drawback is overcome in the O'Connor method.<sup>19</sup>

Photosynthesis depends on many factors, such as sunlight, temperature, mass of algae present, and nutrients. If the effects of these factors are included in the term  $P_t$ , which represents the overall rate at which oxygen is released by photosynthesis, and if the photosynthetic

rate is assumed to vary with the amount of sunlight (reaching a peak at noon and a zero value at sunset and sunrise), then this source of oxygen could be defined by a periodic function<sup>20</sup> such as the following:

$$P_t' = \begin{cases} P_m \sin \frac{\pi}{p} t' & \text{when } 0 \leq t' < p \\ 0 & \text{when } 1 - p \leq t' \end{cases} \quad [\text{Eq 49}]$$

where  $p$  is the period of oscillation of the periodic function,  $p_m$  is the amplitude of the periodic function, and  $t$  is the time of flow in days of a mass of water since sunrise after the mass of water has entered the head end of the river reach being considered. Figure 5 illustrates this periodic function.

If the period of oscillation,  $p$ , is taken as 12 hours or half a day, the periodic function shown in Eq 49 reduces to

$$P_t' = \begin{cases} P_m \sin 2\pi t' & \text{when } 0 \leq t' \leq 1/2 \\ 0 & \text{when } 1/2 \leq t' \leq 1 \end{cases} \quad [\text{Eq 50}]$$

This periodic function can be represented quite accurately by the first three terms of the Fourier Series, as shown below.

$$P_t' \approx \frac{P_m}{\pi} + \frac{P_m}{2} \sin 2\pi t' - \frac{2P_m}{3\pi} \cos 4\pi t' \quad [\text{Eq 51}]$$

This approach of expressing the diurnal variations in photosynthetic activity quantitatively is decidedly superior to averaging them over the entire period, which would include the nighttime flow conditions.

Using this expression (Eq 51) for photosynthetic oxygen addition, the oxygen balance equation becomes

$$\frac{dD}{dt} = K_c L_{uc} e^{-K_c t} + K_n L_{un} e^{-K_n(t-t_0)} - K_2 D - P_m \left( \frac{1}{\pi} + 1/2 \sin 2\pi t' - \frac{2}{3\pi} \cos 4\pi t' \right) + R \quad [\text{Eq 52}]$$

where  $R$  is the rate of respiration (mg/l/day) of the aquatic biota and all the other terms are as defined earlier.

<sup>20</sup>O'Connor and Dobbins.

<sup>18</sup>T. Gaardner and H. H. Gran, "Investigations of the Production of Plankton in the Oslo Fjord," *Conseil Permanent Internat. Explor. Mer. Process. Verbaux Reunione*, Vol 42 (1927), pp 1-48.

<sup>19</sup>D. J. O'Connor and W. E. Dobbins "Mechanisms of Reaeration in Natural Streams," *Trans. ASCE*, Vol 123 (ASCE, 1959).

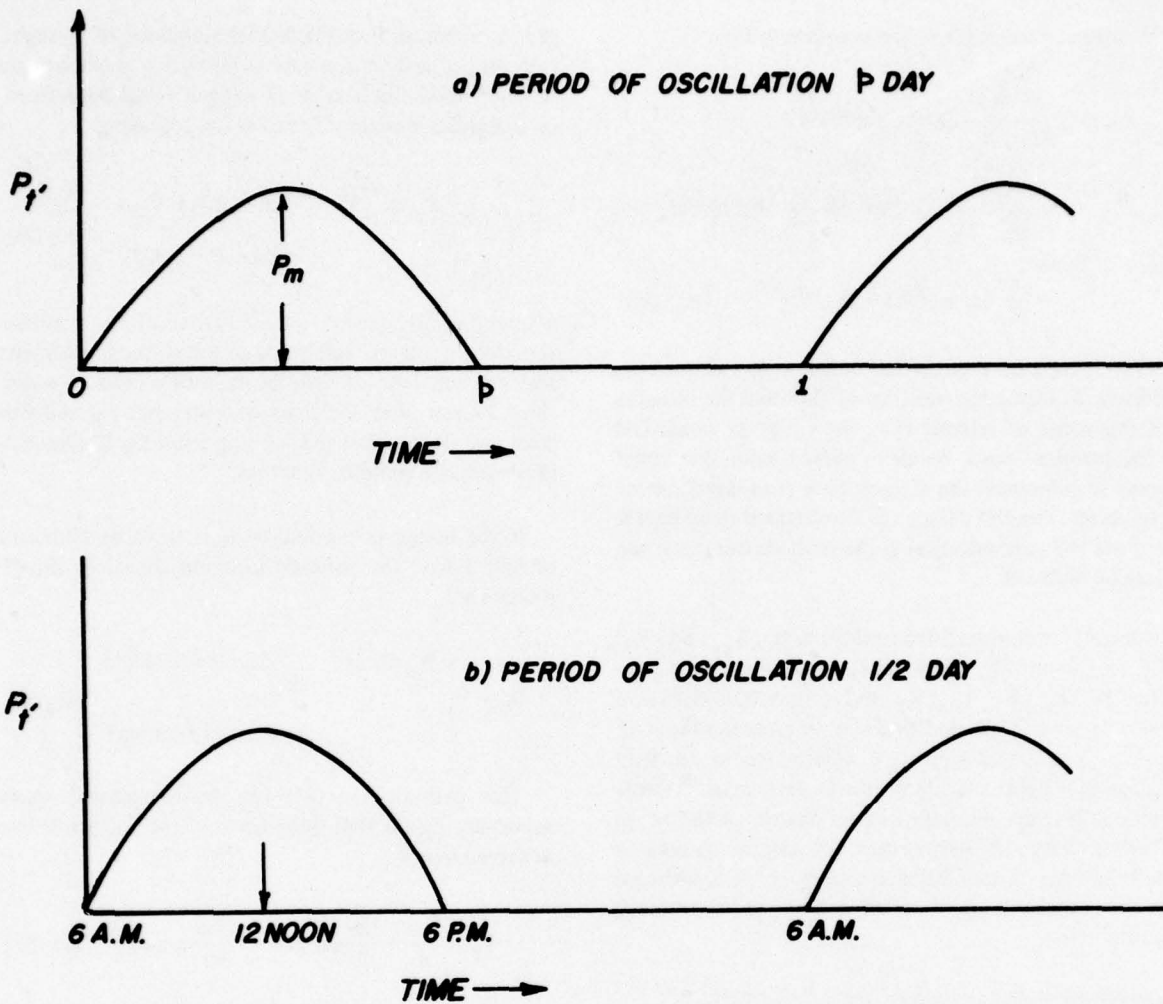


Figure 5. The periodic function.

The solution to this differential equation is

$$\begin{aligned}
 De^{K_2 t} = & \frac{K_c L_{uc}}{K_2 - K_c} e^{(K_2 - K_c)t} \\
 & + \frac{K_n L_{un}}{K_2 - K_n} e^{K_2 t - K_n(t-t_0)} - \frac{P_m}{\pi K_2} e^{K_2 t} \\
 & - \frac{P_m e^{K_2 t}}{2(K_2^2 + 4\pi^2)} [K_2 \sin 2\pi t' - 2\pi \cos 2\pi t'] \\
 & + \frac{2P_m}{3\pi} \cdot \frac{e^{K_2 t}}{K_2^2 + 16\pi^2} [4\pi \sin \pi t' + K_2 \cos 4\pi t'] \\
 & + \frac{R e^{K_2 t}}{K_2} + \text{constant} \quad [\text{Eq 53}]
 \end{aligned}$$

Applying the initial conditions of  $D = D_0$  when  $t = 0$ ,

$$\begin{aligned}
 \text{Constant} = D_0 - & \frac{K_c L_{uc}}{K_2 - K_c} - \frac{K_n L_{un}}{K_2 - K_n} e^{K_n t_0} + \frac{P_m}{\pi K_2} \\
 & + \frac{P_m}{2(K_2^2 + 4\pi^2)} [K_2 \sin 2\pi \tau - 2\pi \cos 2\pi \tau] \\
 & - \frac{2P_m}{3\pi(K_2^2 + 16\pi^2)} [4\pi \sin \pi \tau + K_2 \cos 4\pi \tau] \\
 & - \frac{R}{K_2} \quad [\text{Eq 54}]
 \end{aligned}$$

In Eq 54, the term  $\tau$ , in days, is the elapsed time since sunrise (6 AM) for the initial observation, i.e., when  $t' = 0$ ,  $t = \tau$ .

Substituting the value of the constant in Eq 53, the DO deficit equation is given as:

$$\begin{aligned}
 D = & \frac{K_c L_{uc}}{K_2 - K_c} (e^{-K_c t} - e^{-K_2 t}) \\
 & + \frac{K_n L_{un}}{K_2 - K_n} [e^{-K_n(t-t_0)} - e^{-(K_2 t - K_n t_0)}] \\
 & - \frac{P_m}{\pi K_2} (1 - e^{-K_2 t}) + \frac{R}{K_2} (1 - e^{-K_2 t}) \\
 & - \frac{P_m}{2(K_2^2 + 4\pi^2)} [(K_2 \sin 2\pi t' - 2\pi \cos 2\pi t')] \\
 & - e^{-K_2 t} (K_2 \sin 2\pi \tau - 2\pi \cos 2\pi \tau)] \\
 & + \frac{2P_m}{3\pi(K_2^2 + 16\pi^2)} [(4\pi \sin 4\pi t' + K_2 \cos 4\pi t')] \\
 & - e^{-K_2 t} (4\pi \sin \pi \tau + K_2 \cos 4\pi \tau)] \\
 & + D_0 e^{-K_2 t} \quad \text{[Eq 55]}
 \end{aligned}$$

Once the DO deficit is assessed at any point in a given river reach, the dissolved oxygen can be estimated as discussed earlier.

If the BOD resulting from the oxidation of nitrogenous matter, oxygen addition from photosynthesis, and aquatic biota respiration are considered insignificant compared to the two important processes affecting the oxygen balance (the BOD due to the oxidation of carbonaceous matter and the atmospheric reaeration), then the DO deficit equations (Eqs 48 and 55) reduce to the classical form given by Streeter and Phelps.<sup>21</sup>

$$D = \frac{K_c L_{uc}}{K_2 - K_c} (e^{-K_c t} - e^{-K_2 t}) + D_0 e^{-K_2 t} \quad \text{[Eq 56]}$$

<sup>21</sup> H. W. Streeter and E. B. Phelps, "A Study of the Pollution and Natural Purification of the Ohio River," *Public Health Bulletin 146* (U.S. Public Health Service, 1925).

### 3 USE OF THE DOSAG MODEL

#### Batch Mode

DOSAG combines the three analysis functions into one computer program. Ten output options are available to the user, as described in Table 1. To obtain output, the user should first complete the input form (Figure 6), supplying all the required input data. Table 2 defines the required input parameters, and Figure 7 illustrates the format for submitting the paired observations data required for analysis options 2 and 3. The input form should then be mailed to:

US Army CERL/EN  
 ATTN: Bob Riggins  
 P.O. Box 4005  
 Champaign, Illinois 61820

CERL will then put the data into the format necessary for running it through the computer and mail the resulting output to the user.

Figures 8 through 11 are examples of the types of output available from DOSAG. The test data are fictional and were developed to illustrate as many options as possible.

#### Conversational Mode

A computer program operating in conversational mode prompts the user for input data and option selection. The user is given a list of nine options from which to choose; he/she types "1" if the option is chosen, or "0" if it is not. Following are the available options.

OPTION 1—USE OBSERVED DATA TO CALC COEFF FOR SINUSOIDAL ANNUAL WATER TEMP CURVE IF DESIRED TYPE 1 IF NOT 0

OPTION 2—USE OBSERVED DATA TO CALC CARBONACEOUS DEOXYGENATION COEFF, VIA BOD, TYPE 1 OR 0

OPTION 3—USE OBSERVED DATA TO CALC NITROGENOUS DEOXYGENATION COEFF, VIA BOD, TYPE 1 OR 0

OPTION 4—CALC DISSOL OXYGEN SAG FOR A SINGLE REACH OF STREAM WITH ONE WASTE DISCHARGE, VIA DO, TYPE 1 OR 0

**Table 1**  
DOSAG Options

Option	Description
1	Calculate a dissolved oxygen profile for a single reach of stream with one waste inflow, considering only carbonaceous deoxygenation demand.
2	Include nitrogenous deoxygenation demand in the calculations for dissolved oxygen profile.
3	Use Churchill method for reaeration. If this option is not specified, the Langbien-Durum equation will be used.
4	Include photosynthesis deoxygenation in the calculations for dissolved oxygen profile using Camp's method.
5	Include photosynthesis deoxygenation using O'Connor's method.
6	Use sinusoidal curve coefficients (which have been previously determined) to calculate water temperature for use in determining dissolved oxygen profile.
7	Use with option 10 to specify a day for which a temperature value is to be calculated. This temperature value will be used if option 1 is selected.
8	Use observed data to calculate a carbonaceous deoxygenation rate coefficient and ultimate biochemical oxygen demand. (If option 1 is also chosen, these parameters will become input data to the calculations for dissolved oxygen profile.)
9	Use observed data to calculate a nitrogenous deoxygenation rate coefficient and ultimate biochemical oxygen demand. (If options 1 and 2 are also chosen, these parameters will become input data to the calculations for dissolved oxygen profile.)
10	Use observed data to calculate coefficients for sinusoidal annual water temperature curve. (If option 1 is also chosen, a value for water temperature will become input data for calculations of dissolved oxygen profile.)

**Table 2**  
Parameter Definitions

Parameter	Definition
1.1 UPSTQ	Upstream flow (cfs)
1.2 UPSTDO	Upstream dissolved oxygen (mg/l)
1.3 UPSBODC	Upstream carbonaceous deoxygenation demand (mg/l)
1.4 EFFQ	Effluent flow (cfs)
1.5 EFFDO	Effluent dissolved oxygen (mg/l)
1.6 EFFBODC	Effluent carbonaceous deoxygenation demand (mg/l)
1.7 WIDTH	Average stream width (ft)
1.8 DEPTH	Average stream depth (ft)
1.9 DISTC	Length of the stream reach (miles)
1.10 KSUBC	Carbonaceous deoxygenation rate coefficient
1.11 TEMP	Water temperature (°C)
2.1 UPSBODN	Upstream nitrogenous deoxygenation demand (mg/l)
2.2 EFFBODN	Effluent nitrogenous deoxygenation demand (mg/l)
2.3 KSUBN	Nitrogenous deoxygenation rate coefficient
2.4 TZERO	Time lag for nitrogenous deoxygenation demand (days)
4.1 PSUBM	Amplitude of the photosynthesis periodic function
4.2 RESP	Rate of respiration (mg/l/day)
4.3 TALL	Time of flow (days) since sunrise after the mass of water has entered the head end of a river reach
5.1 A	Oxygenation rate due to photosynthesis (mg/l/day)
6.1 P	Sinusoidal water temperature curve coefficient
6.2 Q	Sinusoidal water temperature curve coefficient
6.3 TBAR	Average water temperature (°C)
6.4 DAY	Day of year (Julian)
7.1 DAY	Day of year (Julian)
8.1 EKSUBC	Estimated carbonaceous deoxygenation rate coefficient
Paired Observations	Observed values of carbonaceous BOD (mg/l) over time (days) determined by laboratory analysis
9.1 EKSUBN	Estimated nitrogenous deoxygenation rate coefficient
Paired Observations	Observed values of nitrogenous BOD (mg/l) over time (days) determined by laboratory analysis

**DIRECTIONS** – Check the options required and provide the necessary input information. Mail the completed input form to:

US Army CERL/EN  
 P. O. Box 4005  
 Champaign, IL 61820

DATE \_\_\_\_\_  
 NAME \_\_\_\_\_  
 ADDRESS \_\_\_\_\_  
 PHONE \_\_\_\_\_

- Notes:
1. Options 2-7 require option 1.
  2. Option 7 also requires option 10.
  3. Values 1.6 and 1.10 can be furnished by option 8.
  4. Value 1.11 can be furnished by option 6 or 7.
  5. Values 2.2 and 2.3 can be furnished by option 9.
  6. Paired observations data should be submitted on a separate data sheet such as that illustrated in Figure 7 of the user manual.

Option 1

1.1 UPSTQ _____	1.4 EFFQ _____	1.7 WIDTH _____
1.2 UPSTDO _____	1.5 EFFDO _____	1.8 DEPTH _____
1.3 UPSBODC _____	1.6 EFFBODC _____	1.9 DISTC _____
1.10 KSUBC _____	1.11 TEMP _____	

Option 2

2.1 UPSBODN \_\_\_\_\_  
 2.2 EFFBODN \_\_\_\_\_  
 2.3 KSUBN \_\_\_\_\_  
 2.4 TZERO \_\_\_\_\_

Option 4

4.1 PSUBM \_\_\_\_\_  
 4.2 RESP \_\_\_\_\_  
 4.3 TAU \_\_\_\_\_

Option 6

6.1 P \_\_\_\_\_  
 6.2 Q \_\_\_\_\_  
 6.3 TBAR \_\_\_\_\_  
 6.4 DAY \_\_\_\_\_

Option 3

Option 5

5.1 A \_\_\_\_\_

Option 7

7.1 Day \_\_\_\_\_

Option 8

8.1 EKSUBC \_\_\_\_\_  
 Paired Observations:  
 8.2 times  
 8.3 BODC values

Option 9

9.1 EKSUBN \_\_\_\_\_  
 Paired Observations:  
 9.2 times  
 9.3 BODN values

Option 10

Paired Observations  
 10.1 Days  
 10.2 Temp. values

**Figure 6.** Input form for DOSAG.



ENVIRONMENTAL DIVISION  
CONSTRUCTION ENGINEERING RESEARCH LABORATORY  
UNITED STATES ARMY CORPS OF ENGINEERS

ANALYTICAL TECHNIQUES FOR ENVIRONMENTAL IMPACT ANALYSIS  
WATER QUALITY ANALYSIS SYSTEMS  
DOSAG COMPONENT  
SEPTEMBER 1977 VERSION

O U T P U T F O R :

BAYOU ANACOCO - FORT POLK, LA

ANALYSIS OPTIONS SELECTED:

T -- USE OBSERVED DATA TO CALCULATE COEFFICIENTS FOR SINUSOIDAL ANNUAL WATER TEMPERATURE CURVE AND, IF DO IS TO BE COMPUTED CALCULATE WATER TEMPERATURE FOR A GIVEN DAY OF THE YEAR VIA STEMP1

C -- USE OBSERVED DATA TO CALCULATE CARBONACEOUS DEOXYGENATION COEFFICIENT VIA BOD

N -- USE OBSERVED DATA TO CALCULATE NITROGENOUS DEOXYGENATION COEFFICIENT VIA BOD

D -- CALCULATE DISSOLVED OXYGEN SAG FOR A SINGLE REACH OF STREAM WITH ONE WASTE DISCHARGE VIA DO. IF C IS SPECIFIED, USE COMPUTED KSUBC. IF Y IS SPECIFIED CONSIDER NITROGENOUS DEOXYGENATION; AND, IF N IS SPECIFIED, USE COMPUTED KSUBN.

A -- USE CHURCHILL'S METHOD FOR REAERATION: OTHERWISE, USE LANGBERN-DURUM EQUATION.

P -- INCLUDE PHOTOSYNTHESIS USING CAMP'S METHOD

Y -- INCLUDE NITROGENOUS DEOXYGENATION IN THE DO SAG CALCULATION.

Figure 8. Example DOSAG output-options selection.

SINUSOIDAL CURVE FITTING FOR OBSERVED WATER TEMPERATURES BY LEAST SQUARE FIT

DAYS FROM INITIAL PERIOD	OBSERVED TEMPERATURE	COMPUTED TEMPERATURE
257.0	26.0	23.8
165.0	27.0	23.8
163.0	26.0	23.7
182.0	27.0	24.5
226.0	28.0	24.9
253.0	24.0	24.0
324.0	13.0	19.3
13.0	7.0	16.8
43.0	11.0	16.8
78.0	16.0	18.1
113.0	24.0	20.4
148.0	26.0	22.8
336.0	20.0	18.5
295.0	22.0	21.4
314.0	15.0	20.0
363.0	18.0	17.2
19.0	10.0	16.7
46.0	13.0	16.9
74.0	20.0	17.9
116.0	19.0	20.6
137.0	24.0	22.1
165.0	28.0	23.8
228.0	26.0	24.8
207.0	23.0	25.0
196.0	24.0	24.9
269.0	23.0	23.1
196.0	23.0	24.9

AMPLITUDE = 4.2  
 STAND. ERROR = 3.7  
 STAND. DEV. = 6.0  
 COEFF. of CORR. = .794

CURVE COEFF. AND AVE. ANNUAL TEMP  
 A = -1.934  
 Q = -3.698  
 TBAR = 20.852

CALCULATED TEMP FOR DAY 95. IS 19.2

Figure 9. Example DOSAG output-temperature.

CARBONACEOUS BOD PROGRESSION INPUT DATA

TIME IN DAYS	BOD SATISFIED
.990	2.420
1.860	4.190
2.950	5.600
4.850	7.020
6.820	8.250
8.860	9.230

CARBONACEOUS RATE COEFF. = .279  
CARB. ULT. BOD = 9.834

NITROGENOUS BOD PROGRESSION INPUT DATA

TIME IN DAYS	BOD SATISFIED
3.000	2.420
4.000	4.190
5.000	5.600
7.000	7.020

NITROGENOUS RATE COEFF. = .333  
NITR. ULT. BOD = 8.703

COMPUTED TOTAL BOD PROGRESSION

TIME IN DAYS	TOTAL BOD SATISFIED
0.000	0.000
.500	1.282
1.000	2.398
1.500	3.367
2.000	4.210
2.500	4.944
3.000	5.581
3.500	6.136
4.000	6.618
4.500	7.037
5.000	7.402
5.500	7.719
6.000	7.995
6.500	8.235
7.000	8.443
7.500	8.625
8.000	8.782
8.500	8.919
9.000	9.039
9.500	9.142
10.000	9.232

Figure 10. Example DOSAG output-rate coefficients and ultimate biochemical oxygen demand.

CRITERIA FOR COMPUTATION OF DO DEFICIT

UPSTREAM FLOW= 21.000    EFFLUENT FLOW= 4.800  
 UPSTREAM BODC= 2.000    EFFLUENT BODC= 9.834  
 UPSTREAM DO= 7.000    EFFLUENT DO= .700  
 WIDTH= 35.000  
 DEPTH= 3.000  
 KSUBC= .269  
 TEMP= 19.155  
 DISTANC= 50.000

UPSTREAM BODN= 2.000    EFFLUENT BODN= 8.703  
 KSUBN= .308  
 TZERO= 2.000

RECREATION RATE COEFFICIENT= .435

A-VALUE FOR CAMP'S PHOTOSYNTHESIS IS, .100

DISSOLVED OXYGEN PROFILE FOR DISTANCE OF 50.00 MILES

TIME IN DAYS	DISTANCE IN MILES	DO. DEFICIT	DISS. OXYGEN
0.00	0.00	3.35	5.83
.20	.80	3.13	6.05
.40	1.61	2.93	6.25
.60	2.41	2.74	6.44
.80	3.22	2.56	6.62
1.00	4.02	2.39	6.79
1.20	4.82	2.23	6.95
1.40	5.63	2.09	7.09
1.60	6.43	1.95	7.23
1.80	7.24	1.82	7.36
2.00	8.04	1.70	7.48
2.20	8.85	3.39	5.79
2.40	9.65	3.31	5.87
2.60	10.45	3.22	5.96
2.80	11.26	3.13	6.05
3.00	12.06	3.03	6.15
3.20	12.87	2.93	6.25
3.40	13.67	2.83	6.35
3.60	14.47	2.73	6.45

Figure 11. Example DOSAG output-DO deficit.

TIME IN DAYS	DISTANCE IN MILES	DO. DEFICIT	DISS. OXYGEN
3.80	15.28	2.62	6.55
4.00	16.08	2.52	6.66
4.20	16.89	2.42	6.76
4.40	17.69	2.32	6.86
4.60	18.50	2.22	6.96
4.80	19.30	2.12	7.06
5.00	20.10	2.03	7.15
5.20	20.91	1.93	7.24
5.40	21.71	1.84	7.34
5.60	22.52	1.75	7.42
5.80	23.32	1.67	7.51
6.00	24.12	1.58	7.59
6.20	24.93	1.50	7.68
6.40	25.73	1.43	7.75
6.60	26.54	1.35	7.83
6.80	27.34	1.28	7.90
7.00	28.15	1.21	7.97
7.20	28.95	1.14	8.04
7.40	29.75	1.07	8.11
7.60	30.56	1.01	8.17
7.80	31.36	.95	8.23
8.00	32.17	.89	8.29
8.20	32.97	.84	8.34
8.40	33.77	.79	8.39
8.60	34.58	.74	8.44
8.80	35.38	.69	8.49
9.00	36.19	.64	8.54
9.20	36.99	.60	8.58
9.40	37.80	.56	8.62
9.60	38.60	.52	8.66
9.80	39.40	.48	8.70
10.00	40.21	.44	8.74
10.20	41.01	.41	8.77
10.40	41.82	.37	8.81
10.60	42.62	.34	8.84
10.80	43.42	.31	8.87
11.00	44.23	.28	8.90
11.20	45.03	.26	8.92
11.40	45.84	.23	8.95
11.60	46.64	.21	8.97
11.80	47.45	.18	9.00
12.00	48.25	.16	9.02
12.20	49.05	.14	9.04
12.40	49.86	.12	9.06
12.44	50.00	.12	9.06

Figure 11. (con't)

**OPTION 5—USE CHURCHILL'S METHOD FOR REAERATION OTHERWISE USE LANGBIEN-DURUM, TYPE 1 OR 0**

**OPTION 6—INCLUDE PHOTOSYNTHESIS USING CAMPS METHOD, TYPE 1 IF DESIRED, IF NOT TYPE 0**

**OPTION 7—INCLUDE PHOTOSYN USING O'CONNOR'S METHOD TYPE 1 OR 0**

**OPTION 9—COMPUTE TEMP GIVEN THE EQUATION COEFF, MEAN ANN TEMP, + DAY OF YEAR, TYPE 1 OR 0**

The user should first obtain the required input data for the options he/she will select.

The model can then be accessed through telephone hook-up, using a remote terminal.

The interactive user may access the system by completing four tasks:

(1) Setting remote terminal settings. (Full duplex, 30 cps, online)

(2) Dialing the appropriate computer number. Two numbers are presently available: (Commercial: 217/333-1587 and FTS: 957-1587)

(3) Logging into the computer by typing the user name and the appropriate password. Following is an example of user response.

CAC Network Unix System

log in: riggins

Password: \_\_\_\_\_

In response to the "password" request, the user supplies the appropriate response. (The password will not be printed on the output page.) The user may obtain a password by contacting CERL/EN; ATTN: Bob Riggins, P.O. Box 4005, Champaign, IL 61820.

System messages will appear next, as in the following example.

15 Apr 76 UNIX rp0 dump will be done between 1700-1800 tonight.

The System will go down at 1655; please be off by then.

New System testing periods. .run bullboard.

Issty: not found

No mail

This account has been changed to accommodate added systems.

Type "dosag" to get into CERL's programs.

These messages are only for relaying system information to users. Any changes in CERL's ETIS approach will be identified here. The user should wait for a response from the computer before entering additional commands. This signal will be the character "%."

(4) Logging into the DOSAG model:

% dosag

The following are program prompts as they appear in the options in the DOSAG model program.

**OPTION 1—USE OBSERVED DATA TO CALC COEFF FOR SINUSOIDAL ANNUAL WATER TEMP CURVE IF DESIRED TYPE 1 IF NOT 0**

Option 1 calculates the coefficient for sinusoidal annual water temperature curve. If this option is desired, the correct user response is 1. Option 1 requires that the user provide responses to three data requests.

1. Enter the number of observations for the year being analyzed.

2. Enter the Julian number for each day for which a temperature observation is used. When finished, type 999.

3. Enter the observed temperature corresponding to each given Julian number. When finished, type 999.

Data requests 2 and 3 may require more than one response. If so, the user should enter a different value on each line, depressing the carriage return after each value, and typing 999 when all values are entered. The user should insure that the sequence of temperature entries corresponds to the sequence of day values.

**OPTION 2—USE OBSERVED DATA TO CALC CARBONACEOUS DEOXYGENATION COEFF, VIA BOD, TYPE 1 OR 0**

Option 2 calculates the carbonaceous deoxygenation coefficient. If this option is desired, the correct user response is 1. Option 2 requires the user to provide responses to five data requests.

1. Enter the total number of BOD observations for carbonaceous demand.

2. Enter initial estimate for carbonaceous rate coefficient.

3. Enter TZERO.

4. Enter each day of carbonaceous demand observation in numerical sequence. When finished, type 999.

5. Enter each BOD carbonaceous demand observation in sequence corresponding to day of observation. When finished, type 999.

Data requests 4 and 5 may require more than one response. If so, the user enters a different value on each line, depressing the carriage return after each value, and typing 999 when finished.

**OPTION 3—USE OBSERVED DATA TO CALC NITROGENOUS DEOXYGENATION COEFF, VIA BOD, TYPE 1 OR 0**

Option 3 calculates the nitrogenous deoxygenation coefficient and may not be selected without first selecting option 2. Option 3 requires that the user provide responses to nine data requests.

1. Enter total number of BOD observations for carbonaceous demand.

2. Enter total number of BOD observations for nitrogenous demand.

3. Enter carbonaceous rate coefficient.

4. Enter nitrogenous rate coefficient.

5. Enter TZERO.

6. Enter day of carbonaceous demand observation. When finished, type 999.

7. Enter BOD carbonaceous demand. When finished, type 999.

8. Enter day of nitrogenous demand observation. When finished, type 999.

9. Enter nitrogenous demand. When finished, type 999.

Data requests 6, 7, 8, and 9 may require more than one response. If so, the user enters a different value on each line, depressing the carriage return after each value, and typing 999 when finished.

**OPTION 4—CALC DISSOL OXYGEN SAG FOR A SINGLE REACH OF STREAM WITH ONE WASTE DISCHARGE, VIA DO, TYPE 1 OR 0**

Option 4 calculates the dissolved oxygen sag for a single reach of stream with one waste discharge. This option requires that the user provide responses to 11 data requests.

1. Enter effluent BODC.

2. Enter KSUBC.

3. Enter upstream flow.

4. Enter effluent flow.

5. Enter upstream BODC.

6. Enter upstream DO.

7. Enter effluent DO.

8. Enter stream width (in feet).

9. Enter stream depth (in feet).

10. Enter stream temperature (in °C).

11. Enter distance (in miles).

**OPTION 5—USE CHURCHILL'S METHOD FOR REAERATION OTHERWISE USE LANGBIEN-DURUM, TYPE 1 OR 0**

A "1" response to Option 5 enables the use of Churchill's method for reaeration; a "0" response provides the Langbien-Durum method. This option is used in conjunction with option 4 and may not be used unless a "1" response has been given to option 4. There are no additional data requests for option 4.

**OPTION 6—INCLUDE PHOTOSYNTHESIS  
USING CAMP'S METHOD, TYPE 1  
IF DESIRED, IF NOT TYPE 0**

Option 6 output includes the photosynthesis calculations using Camp's method for finding dissolved oxygen sag. This option may only be used in conjunction with option 4 and may not be used unless a "1" response has been given to option 4. In addition to the data requests for option 4, the following input is also required.

Enter A-Value for Camp Photosynthesis

**OPTION 7—INCLUDE PHOTOSYN USING  
O'CONNOR'S METHOD, TYPE 1 OR 0**

Option 7 output includes the photosynthesis calculations using O'Connor's method for finding dissolved oxygen sag. This option may only be used in conjunction with a "1" response to option 4. In addition to the data requests for option 4, the following input is also required:

1. Enter amplitude.
2. Enter rate of respiration.
3. Enter TAU.

**OPTION 8—INCLUDE NITROG DEOXYGENATION  
IN DOSAG CALC, TYPE 1 OR 0**

Option 8 output includes nitrogenous deoxygenation calculations for dissolved oxygen sag. This option may only be used in conjunction with a "1" response to option 4. In addition to the data requests for option 4, the following input is also required:

1. Enter upstream BODN.
2. Enter effluent BODN.
3. Enter KSUBN.
4. Enter TZERO.

**OPTION 9—COMPUTE TEMP GIVEN  
THE EQUATION COEFF, MEAN ANN  
TEMP, + DAY OF YEAR, TYPE 1 OR 0**

Option 9 computes the temperature for a specific day when the user provides the equation coefficients,

mean annual temperature, and day of year. This option may not be selected separately, but may be used in conjunction with a "1" response to either options 1 or 2. In addition to the data requests for options 1 or 2, the following input is also required:

1. Enter curve coefficient P.
2. Enter curve coefficient Q.
3. Enter average annual temperature (in °C).
4. Enter the Julian day for which temperature will be calculated.

The examples beginning on page 31 show the procedures for using options 4 and 2, respectively. Output for each example is shown.

## **4 USE OF OUTPUT**

Output from the model can be used to quantify the impact on a stream's dissolved oxygen resources resulting from an Army activity which introduces to the stream material exerting a biological oxygen demand. Options within the model provide intermediate calculations of values for parameters such as water temperature, deoxygenation rate coefficients, and ultimate biological oxygen demand which may be needed to compute the DO sag curve. The model is applicable for a single-reach, single-point-source pollutant inflow situation. The flow conditions must correspond to a steady-flow-state.

The resulting DO sag curve profile can be used to determine the following:

1. The minimum DO level
2. The stream location where DO is a minimum
3. The stream location where DO level recovers to specified levels (saturation level or quality target level).

Analysis of this information will indicate the magnitude of impact on the stream's DO resources.

Example 1

% DOSAG

OPTION 1--USE OBSERVED DATA TO CALC COEFF  
FOR SINUSOIDAL ANNUAL WATER TEMP CURVE  
IF DESIRED TYPE 1 IF NOT 0

0

OPTION 2--USE OBSERVED DATA TO CALC CARBONACEOUS  
DEOXYGENATION COEFF. VIA BOD. TYPE 1 OR 0

0

OPTION 3--USE OBSERVED DATA TO CALC NITROGENOUS  
DEOXYGENATION COEFF. VIA BOD. TYPE 1 OR 0

0

OPTION 4--CALC DISSOL OXYGEN SAG FOR A SINGLE  
REACH OF STREAM WITH ONE WASTE DISCHARGE VIA DO. TYPE 1 OR 0

1

OPTION 5--USE CHURCHILL'S METHOD FOR REAERATION  
OTHERWISE USE LANGBERN-DURUM. TYPE 1 OR 0

0

OPTION 6--INCLUDE PHOTOSYNTHESIS USING CAMPS METHOD.  
TYPE 1 IF DESIRED, IF NOT TYPE 0

0

OPTION 7--INCLUDE PHOTOSYN USING O'CONNOR'S METHOD  
TYPE 1 OR 0

1

OPTION 8--INCLUDE NITROG DEOXYGENATION IN DOSAG CALC  
TYPE 1 OR 0

0

OPTION 9--COMPUTE TEMP GIVEN THE EQUATION COEFF, MEAN  
ANN TEMP, + DAY OF YEAR. TYPE 1 OR 0

0

ENTER EFFLUENT BODC

2

ENTER KSUBC

2

ENTER UPSTREAM FLOW

2

ENTER UPSTREAM BODC

3

ENTER UPSTREAM DO

11

ENTER EFFLUENT DO

3

ENTER STREAM WIDTH

5

ENTER STREAM DEPTH

2

ENTER STREAM TEMP(IN C)

21

ENTER DISTANCE(IN MILES)

4

CRITERIA FOR COMPUTATION OF DO DEFICIT

INPUT VALUES

UPSTREAM FLOW 2.000000

EFFLUENT FLOW 2.000000

UPSTREAM BODC 3.000000

RECREATION RATE COEFFICIENT 1.498322

ENTER VALUES FOR O'CONNORS PHOTOSYNTHESIS

ENTER AMPLITUDE

2

ENTER RATE OF RESPIRATION

3

ENTER TAU

2

DISSOLVED OXYGEN PROFILED FOR DIST OF 4.000000 MILES

TIME IN DAYS	DIST IN MILES	DO DEFICIT	DISS OXYGEN
0.000000	0.000000	-5.444165	14.285311
0.200000	1.309088	-2.965776	11.806922
0.400000	2.618176	-1.493284	10.334430

Example 2

% DOSAG

OPTION 1--USE OBSERVED DATA TO CALC COEFF  
FOR SINUSOIDAL ANNUAL WATER TEMP CURVE  
IF DESIRED TYPE 1 IF NOT 0

0

OPTION 2--USE OBSERVED DATA TO CALC CARBONACEOUS  
DEOXYGENATION COEFF. VIA BOD. TYPE 1 OR 0

1

OPTION 3--USE OBSERVED DATA TO CALC NITROGENOUS  
DEOXYGENATION COEFF. VIA BOD. TYPE 1 OR 0

0

OPTION 4--CALC DISSOL OXYGEN SAG FOR A SINGLE  
REACH OF STREAM WITH ONE WASTE DISCHARGE VIA DO. TYPE 1 OR 0

0

OPTION 5--USE CHURCHILL'S METHOD FOR REAERATION  
OTHERWISE USE LANGBIEN-DURUM. TYPE 1 OR 0

0

OPTION 6--INCLUDE PHOTOSYNTHESIS USING CAMPS METHOD.  
TYPE 1 IF DESIRED, IF NOT TYPE 0

0

OPTION 7--INCLUDE PHOTOSYN USING O'CONNOR'S METHOD  
TYPE 1 OR 0

0

OPTION 8--INCLUDE NITROG DEOXYGENATION IN DOSAG CALC  
TYPE 1 OR 0

0

OPTION 9--COMPUTE TEMP GIVEN THE EQUATION COEFF, MEAN  
ANN TEMP, + DAY OF YEAR. TYPE 1 OR 0

0

ENTER TOTAL # OF BOD OBSERVATIONS FOR CARBONACEOUS DEMAND

3

ENTER TOTAL # OF BOD OBSERVATIONS FOR NITROGENOUS DEMAND

3

ENTER CARBONACEOUS RATE COEFF

.2

ENTER NITROGENOUS RATE COEFF

.4

ENTER TZERO

3

ENTER DAY OF OBSERVATION OF CARB, DEMAND-WHEN FINISHED TYPE 999

4

5

6

999

ENTER BOD CARB DEMAND - WHEN FINISHED 999

4

5

6

999

ENTER DAY OF OBSER. OF NITROGENOUS DEMAND  
WHEN FINISHED TYPE 999

12

13

14

999

ENTER NITROGENOUS DEMAND  
WHEN FINISHED TYPE 999

7

6

5

999

RATE COEFFICIENTS

CARBONACEOUS BOD PROGRESSION INPUT DATA

TIME IN DAYS	BOD SATISFIED
--------------	---------------

4.000000	4.000000
----------	----------

5.000000	5.000000
----------	----------

6.000000	6.000000
----------	----------

CARBONACEOUS RATE COEFF = 0.012094

CARB ULT BOD 168.773276

COMPUTED TOTAL BOD PROGRESSION

TIME IN DAYS	TOTAL BOD SAT
--------------	---------------

0.000000	0.000000
----------	----------

0.500000	1.017458
----------	----------

1.000000	2.028783
----------	----------

1.500000	3.034011
----------	----------

2.000000	4.033179
----------	----------

END OF MODEL

% DOSAG

## 5 CONCLUSIONS AND RECOMMENDATIONS

This report has described a basic water quality model which can be used to quantify impact on the DO content of a stream resulting from inflow from Army activities. The model is limited to only the DO aspects of the stream. The model is applicable for a single-reach, single-point-source (as opposed to area sources) pollutant inflow situation; in addition, the flow conditions in a stream must correspond to a steady-flow state. This water quality model is applicable to the type of stream conditions prevalent in military installation watersheds.

It is recommended that Army environmental planners and decision-makers use this analytical model for quantifying impact of new Army projects and activities on dissolved oxygen aspects of water quality.

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Riggins, Robert E.

Basic analytical model for environmental impact assessment of surface water resources :  
DOSAG user manual / by R. E. Riggins, V. Kothandaraman, B. C. Goettel. -- Champaign,  
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