METHODS OF DISSOLVED OXYGEN BUDGET ANALYSIS FOR ASSESSING EFFECTS OF DREDGED MATERIAL DISPOSAL ON BIOLOGICAL COMMUNITY METABOLISM

by

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1. The Contract Report transmitted herewith represents the results of one of several research efforts completed as part of Task 1D (Effects of Dredging and Disposal on Aquatic Organisms) of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 1D is included as part of the Environmental Impact and Criteria Development Project of the DMRP, which, among other considerations, includes developing techniques for evaluating the effects of dredging on the water quality and biological productivity of disposal areas.

2. This research was a part of Work Unit 1D04, Application of Simulated Ecosystem Modeling to Dredged Material Research (Phase I), and is indirectly related to Work Unit 1D08, Design and Establishment of an Estuarine Ecosystem Simulation. Specific objectives were to review available water-quality and ecological modeling techniques through literature surveys, to observe ongoing research, to further develop applicable models, and to recommend techniques applicable to various environmental problems associated with dredging and disposal of dredged material. To help complete these objectives, three separate computer programs were developed; these programs pertain to calculation of (a) temporal variation of net productivity in flowing water (rivers), (b) depth-averaged net productivity for a standing water body, and (c) the depth distribution of net productivity in standing waters.

3. This report describes procedures for automated, in situ monitoring of biological productivity and the dissolved oxygen budget of aquatic systems and indicates how these techniques might be used for detecting the biological effects of dredged material disposal. Computer programs necessary to implement the methods are presented, and their use is discussed. The study was accomplished under contract with the University of Virginia. The primary objective of the study was to produce data analysis techniques to be used in field and laboratory research efforts of the DMRP. However, the techniques are applicable to specific project studies where dissolved oxygen concentrations are being monitored, and an analysis of the dissolved oxygen budget and biological
productivity is required for assessing environmental effects of engineering activities. These methods are particularly well suited for use with continuous automatic water-quality data-acquisition systems which are receiving increasingly widespread use by field offices.

4. The techniques developed by this study are considered applicable primarily to projects where significant environmental effects are anticipated and a detailed study is required for environmental impact assessment or permit evaluation. The computer programs necessary to apply the methods are operational on the WES computer system. The computer programs and assistance in specifying appropriate data acquisition and analysis procedures for specific applications are available upon request.

G. H. HILT
Colonel, Corps of Engineers
Director
Three computer programs for calculating a continuous function (a Fourier series) describing net community productivity in aquatic environments using measurements of dissolved oxygen concentration, temperature, and salinity with a solution to the oxygen mass balance equation were prepared. These respectively pertain to calculation of (a) temporal variation of net productivity in flowing waters (rivers), (b) depth-averaged net productivity for...
a standing water body, and (c) the depth distribution of net productivity in standing waters. These methods are particularly well suited to use with continuous automatic data recording. Because continuous monitoring of community productivity and respiration provides a direct measure of the biological effects of water quality change, the methods can be useful in assessing effects of dredging and disposal on aquatic communities.
The work described in this report was performed under Contract No. DACW-39-74-C-0030, 2 Oct 1973, between the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, and University of Virginia. The research was sponsored by the Office, Chief of Engineers (DAEN-CWO-M), under the Civil Works Dredged Material Research Program.

This report presents and discusses the use of computer programs for calculating net biological productivity in aquatic environments. Since community productivity and respiration provide a direct measure of the biological effects of water quality change, the methods can be useful in assessing effects of dredging and disposal on aquatic communities.

The work was conducted by Dr. George M. Hornberger and Dr. Mahlon G. Kelly, Assistant Professors of Environmental Sciences, University of Virginia. Ms. Virginia Hendry did much of the computer programming. The subroutines DECOMP, SOLVE, and SIGN were taken from *Computer Solution of Linear Algebraic Systems* by George E. Forsythe and Cleve B. Moler, 1967, Prentice-Hall, Inc., Englewood Cliffs, N. J.

The contract was initiated and managed by Dr. Rex L. Eley, Chief, Ecosystem Research and Simulation Division, under the general supervision of Dr. John Harrison, Chief, Environmental Effects Laboratory. Drs. John Keeley and Robert Engler were project managers. COL G. H. Hilt was the Director, and Mr. F. R. Brown was Technical Director of the WES.
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METHODS OF DISSOLVED OXYGEN BUDGET ANALYSIS FOR ASSESSING EFFECTS
OF DREDGED MATERIAL DISPOSAL ON BIOLOGICAL
COMMUNITY METABOLISM

PART I: INTRODUCTION

1. Measurement of the direct and indirect effects of dredging and
disposal on biological communities is necessary if water-quality problems
associated with dredged material disposal are to be identified and solu-
tions found. Open-water disposal occurs in a wide variety of environ-
ments and thus both the causes of biological changes and the changes
themselves are diverse. Therefore, methods of measuring effects of
dredging and disposal must be very versatile if they are to have wide-
spread applicability. Short-term effects resulting from changes in tur-
bidity, the bottom sediments, and/or oxygen demand as well as long-term
changes associated with release of either biostimulants or toxins must
be sensed.

2. A method for automatically and continuously monitoring commu-
nity productivity and respiration can provide a direct measure of the
biological effects of water quality change. Input of inorganic nutrient-
containing wastes leads to excess photosynthetic production while pollu-
tion by organic material results in an increase in respiration by the
heterotrophic members of a community, producing an excess oxygen demand.
Additionally, toxins may result in a decrease in community productivity,
respiration, or both. Increased turbidity may result in decrease photosyn-
thesis by decreasing available light and any other direct change in
the character of the autotrophs and heterotrophs of the community may
also change net productivity.

3. Most methods for estimating aquatic productivity have depended
on incubation measurements of carbon-14 uptake or free oxygen production,
but errors are caused by containment of the sample, and time resolution
is limited by the incubation period. Attempts to measure productivity
without perturbation by incubation have assumed the rate of change of
free oxygen and inorganic carbon concentration depends almost entirely on community respiration, photosynthesis, physical mixing and transport, and exchange with the atmosphere. Thus it is theoretically possible to measure net community productivity (photosynthesis minus respiration) from the rate of change of inorganic carbon or oxygen concentration if rates of mixing, transport, and exchange with the atmosphere are known. Stated differently, net community productivity can, in theory, be estimated by using a solution of the partial differential equation for oxygen or inorganic carbon mass balance. This avoids errors due to containment and incubation. In the past, attempts to use free concentration measurements have involved problems in accounting for mixing and transport and insolving the mass-balance equation. These attempts have also only been used to give measurements at discrete times or daily mean values.

4. The use of a solution to the oxygen mass-balance equation with measured oxygen concentrations allows calculation of a continuous function (a Fourier series) describing net community productivity. Many of the problems inherent in previous methods of productivity measurement are overcome and a much more detailed analysis of variation of productivity is permitted. The method is also well suited to use with automated data acquisition. This report describes this method for automatically monitoring net productivity and indicates how it might be used for detecting the biological effects of dredging and disposal. The computer programs developed to implement the method are presented and their use is discussed.

5. Dredged material is disposed of on land and in the open ocean, bays, estuaries, and inland rivers and lakes. Disposal on land and in shallow water may be unconfined or confined in diked areas. The measurement of productivity is approached in a different fashion in each of these environments; solution of the mass balance equation forms the basis of the measurements in all cases, but different simplifications of the equation apply in the different environments. To this end three separate computer programs have been developed; the three corresponding equations and their solution are presented on the following pages. These
respectively pertain to calculation of (a) temporal variation of net productivity in flowing water (rivers), (b) depth-averaged net productivity for a standing water body, and (c) the depth distribution of net productivity in standing waters.

6. The major assumptions used in the development of a dissolved oxygen budget have been stated by Odum and Hoskin as: a constant diffusion rate for the 24-hr period; nighttime respiration similar to daytime respiration; one gram of biomass produced for each gram of oxygen released; no turbulent circulation patterns; and similar metabolic history of water entering and leaving an area.

7. Changes induced by dredging and/or disposal in rivers can be monitored by directly using the flowing-water method. A significant disruption of normal biological activity in a river segment can be determined by measuring the productivity of the segment. The second and third methods of determining net productivity pertain to standing waters. When horizontal advection is negligible (e.g., possibly with disposal of dredged material in quiescent lakes and/or bays), the productivity can be calculated using the theory presented below. In certain other situations where advective flows may be important (e.g., a diked disposal site), the average net productivity can be calculated by accounting for the net inflow and outflow of oxygen. The complex hydrodynamics of estuaries makes a meaningful solution of the free-water mass-balance equation impractical with regard to productivity measurement. Therefore monitoring productivity to observe effects of dredging and disposal operations in estuarine waters must be accomplished by containing a sample. The method for measuring productivity in a containerized sample is identical to the technique for obtaining the average productivity of standing waters. Containment may be achieved with large plastic bags, bottles, etc.

8. If these techniques for measuring productivity can be applied in field situations, they can obviously be applied in laboratory studies. Thus, the methods described below can be used for measurement in a variety of environments and in the three major applications for dredged material research cited by Boyd et al.: monitoring programs, field pilot studies, and laboratory studies.
PART II: THEORY

Flowing Water

9. The characteristic equations* of the partial differential equation for oxygen mass balance in a river may be written as

\[ \frac{dx}{dt} = V \quad (1a) \]

\[ \frac{dc}{dt} = K(c_s - c) + P - R \quad (1b) \]

where

- \( x \) = distance downstream (L)
- \( t \) = time (T)
- \( V \) = mean velocity (LT\(^{-1}\))
- \( c \) = oxygen concentration (ML\(^{-3}\))
- \( K \) = reaeration coefficient (T\(^{-1}\))
- \( c_s \) = saturation oxygen concentration (ML\(^{-3}\))
- \( P - R \) = net productivity (ML\(^{-3}\)T\(^{-1}\))

Equation 1b describes the rate of change of dissolved oxygen following the motion of the water. The problem then is to determine \( P - R \) as an explicit function for the segment of river and day under consideration. Since productivity varies with a diurnal period, we may write \( P - R \) as a Fourier cosine series:

\[ P - R = \frac{A_0}{2} + \sum_{n=1}^{\infty} A_n \cos \omega nt \quad (2) \]

where \( A_n \) are the Fourier coefficients and \( \omega = 2\pi/48 \). A cosine series with a 48-hr period was chosen so that values at the beginning

* For convenience, symbols are listed and defined in Notation (Appendix D).
and end of a day are not constrained to be identical. The second 24-hr interval of the cosine expansion is a mirror image of the first 24 hr and is neglected. 8

10. The problem now reduces to determining enough (say, N) Fourier coefficients to accurately describe P - R for a particular day. This may be done by using oxygen concentrations measured at two stations on a river throughout the day to select coefficients so that the integral of Equation 1b accurately predicts the downstream values from the upstream values.

11. If Equation 2 is substituted into Equation 1b and integrated, we have:

$$c_{j+1} = e^{-K\delta} c_j + \frac{1}{e^{Kt_{j+1}}} \int_{t_j}^{t_{j+1}} e^{Kt} c_s(t) \, dt + \frac{A_0}{2K} (1 - e^{-K\delta})$$

$$+ \sum_{n=1}^{N} \frac{A_n}{K^2 + (n\omega)^2} \left( K \cos n\omega t_{j+1} + n\omega \sin n\omega t_{j+1} \right)$$

$$- e^{-K\delta} \left( K \cos n\omega t_j + n\omega \sin n\omega t_j \right) \quad (3a)$$

Time $t_{j+1}$ is the time at which water present at the upstream station at time $t_j$ reaches the downstream station, $\delta$ is the residence time $t_{j+1} - t_j$, $c_j$ is the upstream concentration at time $t_j$, and $c_{j+1}$ is the downstream concentration at time $t_{j+1}$.

12. The Fourier coefficients must be chosen so that Equation 3a accurately predicts measured downstream oxygen concentration from upstream values. If the predicted values are denoted by $c_{j+1}^{(p)}$ and the observed downstream values by $c_{j+1}^{(o)}$ then choice of the $A_n$ to minimize
\[ J = \sum_{j=1}^{M} [c_{j+1}^{(O)} - c_{j+1}^{(P)}]^2 \]  

(3b)

where \( M \) is the number of data points, gives the "best" coefficients (in the least squares sense) for estimating \( P - R \). The function \( J \) depends upon the values of the Fourier coefficients (\( c_{j+1}^{(P)} \) is given by Equation 3a) and minimization may be accomplished by setting the partial derivative of \( J \) with respect to each \( A_n \) equal to zero. The resulting set of linear algebraic equations may be solved for the "best" values of the \( A_n \). A continuous accurate estimate of net productivity may then be obtained by using these coefficients in Equation 2. The net daily production is the 24-hr integral of Equation 3A or simply \( 12A_0 \).

13. The computer program which implements this method is described in Appendix A.

Standing Water

14. A complete mathematical description of the variation of dissolved oxygen concentrations in three spatial dimensions and time is too complex to be used in productivity measurement. In many cases, especially when vertical and temporal free oxygen concentration variations outweigh horizontal variations, a one-dimensional model is useful.

15. The oxygen mass balance equation for standing water may then be derived by applying the principle of conservation of mass to a horizontal slice of the water body. Flows consist of advective inflow and outflow, which are associated with vertical motions, and dispersive flux, which is caused by turbulent mixing and by shear associated with the existing velocity distributions. A term for net productivity must be added to the equation since this is a source or sink of oxygen at any depth. The resulting equation may be written

\[ \frac{3c}{\partial t} + \frac{Q}{A} \frac{2c}{\partial z} = \frac{1}{A} \frac{2c}{\partial z} \left( D_{AV} \frac{2c}{\partial z} \right) + P-R \]  

(4)
where

\( c \) = oxygen concentration (ML\(^{-3}\))
\( t \) = time (T)
\( Q \) = vertical flow (L\(^2\)T\(^{-1}\))
\( A \) = horizontal area (L\(^2\))
\( z \) = vertical distance (L)
\( D_v \) = the vertical dispersion coefficient (L\(^2\)T\(^{-1}\))
\( P-R \) = net community productivity (MT\(^{-1}\))

A further simplification of Equation 4 is obtained if vertical advection is negligible or considered to be accounted for by a dispersion term. The mass-balance equation for oxygen then reduces to

\[
\frac{\partial c}{\partial t} = \frac{\partial}{\partial z} \left( D_v \frac{\partial c}{\partial z} \right) + P-R
\]  

(5)

Equation 5 can be depth averaged to give the equation for calculating the average column net productivity (productivity on an areal basis) in standing waters. The result is

\[
\frac{\overline{\partial c}}{\partial t} = \frac{D_v}{d} \frac{\partial c}{\partial z} \bigg|_0^d + P-R
\]  

(6)

where \( d \) is the total depth (L) and the bar denotes an average over the water column. The first term on the right of Equation 6 accounts for flux across the surface (reaeration) and any exchange of oxygen with the bottom. The surface term can be written as \( \kappa (c_s - c_1)/d \) where \( \kappa \) is the gas exchange coefficient (LT\(^{-1}\)), \( c_s \) is the surface saturation concentration and \( c_1 \) is the actual surface concentration. The exchange with the bottom can be included in the term for net column productivity and Equation 6 written as

\[
\frac{d\overline{c}}{dt} = \frac{K}{d} (c_s - c_1) + \overline{P-R}
\]  

(7)

\( \overline{P-R} \) can be represented as a Fourier cosine series (Equation 2) and \( c_s \) and \( c_1 \) can be treated as measured variables.
Equation 7 can then be integrated to give

\[
\overline{c}_{j+1} = \overline{c}_j + \int_{t_j}^{t_{j+1}} K(c_s - c_1) \, dt + \frac{A_0 \delta}{2} + \sum_{n=1}^{N} \frac{A_n}{n\omega} (\sin n\omega t_{j+1} - \sin n\omega t_j)
\]  

(8)

In this case \( \overline{c}_j \) and \( \overline{c}_{j+1} \) are average concentrations in the one location and are separated in time by \( \delta = t_{j+1} - t_j \).

18. The \( A_n \) may again be determined by minimizing where the predicted values are now given by Equation 8. The computer program which implements this method is described in Appendix B.

19. In some cases calculation of the depth distribution of net productivity may be desirable rather than (or in addition to) calculation of average column productivity. A time-continuous estimate of net productivity at any depth can be obtained by using diurnal oxygen concentrations at that depth, and at depths \( \Delta z \) above and below with a solution to Equation 7. Using the subscript \( i \) to denote depths at which measurements are taken, the dispersion term of Equation 5 can be approximated

\[
\frac{\delta}{\delta z} \left( \frac{\delta c}{\delta z} \right) \approx \frac{1}{(\Delta z)^2} \left[ D_{v_{i+1/2}} c_{i+1} - \left( D_{v_{i+1/2}} + D_{v_{i-1/2}} \right) c_i + D_{v_{i-1/2}} c_{i-1} \right]
\]  

(9)
where

\[ D_{v_{i+1/2}} = \text{the dispersion coefficient between depth } i \text{ and depth } i+1; \quad D_{v_{i-1/2}} \text{ is similarly defined.} \]

20. We can again write P-R as a Fourier cosine series

\[
(P-R)_{i} = \frac{A_{0}^{i}}{2} \sum_{n=1}^{\infty} A_{n}^{i} \cos n \omega t
\]  

where the superscript \( i \) on the Fourier coefficients indicates that the expression refers to productivity at a particular depth.

21. Substituting Equations 9 and 10 into Equation 5 gives the following expression for the rate of change of free oxygen at depth \( i \):

\[
\frac{dc_{i}}{dt} = \frac{1}{(\Delta z)^{2}} \left[ D_{v_{i+1/2}} c_{i+1} + \left( D_{v_{i+1/2}} + D_{v_{i-1/2}} \right) c_{i} + D_{v_{i-1/2}} c_{i-1} \right] + \frac{A_{0}^{i}}{2} + \sum_{n=1}^{\infty} A_{n}^{i} \cos n \omega t
\]

Equation 11 can be treated as an initial value problem in \( c_{i} \) and solved to give:

\[
c_{i}^{j+1} = e^{-U \delta} c_{i}^{j} + \frac{1}{e^{U \delta}_{j+1}} \int_{t_{j}}^{t_{j+1}} (Vc_{i+1} + Wc_{i-1}) e^{Ut} dt + \frac{A_{0}^{i}}{2U} \left( 1 - e^{-U \delta} \right) + \sum_{n=1}^{N} \frac{A_{n}^{i}}{U^{2} + (n \omega)^{2}} \left[ U \cos n \omega t_{j+1} + n \omega \sin n \omega t_{j} \right]
\]  

\[
+ n \omega \sin n \omega t_{j+1} - e^{-U \delta} (U \cos n \omega t_{j} + n \omega \sin n \omega t_{j}) \]  

(12)
where
\[
U = \left( \frac{D_{v_{i+1/2}} + D_{v_{i-1/2}}}{(\Delta z)^2} \right)
\]
\[
V = D_{v_{i+1/2}} \frac{v_{i+1/2}}{(\Delta z)^2}
\]
\[
W = D_{v_{i-1/2}} \frac{v_{i-1/2}}{(\Delta z)^2}
\]

Oxygen exchange at the surface and bottom may be handled in two ways. The flux may be specified, in which case a slight modification of Equation 12 is required; the dispersion flux is replaced with the appropriate known flux. Alternatively, if oxygen measurements near the surface and bottom are used as boundary conditions, the depth-time distribution of P-R may be determined for all but the very top and bottom of the column without the need for determining surface respiration or benthic respiration. In either case the \( A_n \) are again determined by minimizing the sum of squared errors. The computer program for this method is described in Appendix C.
PART III: DATA REQUIREMENTS, INTERPRETATION OF RESULTS, AND USE

22. Inasmuch as the net productivity is calculated from the oxygen mass-balance equation, the primary data required are dissolved oxygen measurements taken frequently enough in space and time to accurately determine the oxygen budget of the system. In rivers this would consist of oxygen measurements at two stations. If the residence time within a river segment is 30 to 90 min, measurements made every 15 to 30 min throughout the day at the ends of the segment should give satisfactory results.1 If the river shows transverse variation in dissolved oxygen (which is very unlikely except in the very largest rivers), several measurements over the cross section should be taken to determine a mean value. In containers and standing water a data interval of 15 to 30 min again seems appropriate. Depth intervals would depend upon the degree of stratification in the particular body of water; for example, Welch12 collected data at 0.25-m increments in Lago pond and Eley13 and Wright14 collected data at 1-m intervals in Keystone Reservoir and Canyon Ferry Reservoir, respectively.

23. In addition to oxygen data, the temperature, salinity, reaeration coefficient, and/or dispersion coefficients may be required, depending upon the situation under study. If the average productivity of a volume of water is desired where inflow and outflow are appreciable (e.g. a diked disposal site), the net advection of oxygen must also be measured and the calculated net productivity suitably corrected.

24. Temperature and salinity are used to calculate the oxygen saturation concentration.15 The value of \( K \), the reaeration coefficient, may be estimated from stream velocity and depth (e.g., see Truesdale et al.15) or by using measured oxygen and radiation values.16 The dispersion coefficients can be estimated from temperature data.9,14

25. Provision of oxygen concentrations, temperature, salinity, reaeration coefficient, and dispersion coefficients as appropriate in the computer programs described in the appendices allows calculation of a time-continuous function describing net productivity. Saturation concentrations are calculated internally in the programs using a polynomial
fit to the data of Truesdale et al. The productivity function in itself can be used in water quality monitoring. For example, the total daily respiration (the oxygen demand of the community) can be calculated by assuming the mean nighttime respiration to be representative for the entire day. P and R can then be calculated separately and the ratio of P:R formed. Most "natural" streams and rivers have shown negative net daily production or a gross production to respiration ratio (P:R) less than one, and the communities thus depend on allochthons energy input. Nutrient enrichment modifies this such that P:R is greater than one and organic material may be exported downstream. A drastic change in P or R may indicate either organic waste or toxin-pollution.

26. If radiation is measured along with the parameters already mentioned, another method of detecting water quality changes via biological activity is available. Kelly et al. showed that a plot of net community productivity for a river versus incident radiation yielded a near-perfect straight-line relationship. The slope of this line is proportional to the production efficiency. This is of course a measure of production independent of light and thus it can be used to determine changes in oxygen demand and production on a day-to-day basis independent of solar radiation.

27. The methods described above thus should allow continuous monitoring of net community productivity of respiration, and of photosynthesis independent of ambient light availability. As discussed in the introduction, these in turn should reflect water quality changes due to dredging activities.

28. Changes in biological community metabolism resulting from dredged material disposal in rivers can be monitored by comparing metabolic characteristics of the perturbed section of the river with metabolic characteristics of a similar but unperturbed section (Figure 1). Data required for this evaluation have already been stated and are summarized in Figure 1. With this information from three sampling stations, comparisons among successive river segments can be made to assess the effects of dredging and disposal operations on the biological community.
Unlike tests which use only indicator organisms or species, the dissolved oxygen budget provides information about total community production and respiration. This technique also permits the establishment of control and treatment areas which are amenable to statistical analysis.

29. The method is equally applicable to standing water (Figure 2). Control and treatment areas can again be established but the minimum number of sampling stations is now reduced to two. For example, the perturbed area represents the treatment and an adjacent and similar area serves as the experimental control. Comparisons among areas can be made on an average column basis using the depth-averaged program or on a depth distribution basis. This latter comparison may be important in stratified waters in determining deoxygenation or increased production (i.e. algal blooms) as a function of depth.
30. The ratio of total community production to respiration (P:R) is one measure of system functioning. In most natural standing waters, this ratio is near 1.0. This ratio can be used to assess the biological condition of the ecosystem. A sustained P:R much greater than 1.0 may indicate a substantial release of nutrients from the dredged material and an associated stimulation of photosynthetic plants. A ratio much less than 1.0 may indicate the release of contaminants such as heavy metals, toxins, or an increase in turbidity which inhibit photosynthetic oxygen production. A return of P:R to near 1.0 may indicate improvement of the quality of the disposal area ecosystem.

31. All of the methods and programs have been tested using simulated data, and the flowing water method has been extensively field tested. The standing water methods should of course be field tested before use for routine monitoring. We particularly recommend that these methods be used with careful automated data acquisition.
REFERENCES


APPENDIX A: FLOWING WATER PROGRAM

Input

1. Definitions of the FORTRAN variables are given in Table A1. The order in which the cards are read and the proper formats are specified in Table A2. The cards are read in the order indicated with several exceptions: (a) card number 1 is not repeated when several days of data are processed together; the information for the second day would begin with card number 2; (b) the data are read according to the operation code (e.g. if KODE is set equal to 3 only upstream data are read and cards N+5 through 2N+5 would be omitted); (c) the last card is necessary only if radiation data are not available (KRAD = 0).

Listing

2. A listing of the computer program follows.

Output

3. Output from the program includes a printout of the input oxygen concentrations, the saturation concentrations, radiation, and the input parameters such as reaeration coefficient, pressure, residence time, etc. The calculated Fourier parameters, the predicted oxygen concentrations, P:R as a function of time and, net daily production, respiration, and gross production are also printed. Line printer graphs of the oxygen values, the net productivity, and productivity versus radiation are also included in the output. Figure A1 shows typical output.

METHOD

THE RATE OF CHANGE OF OXYGEN CONCENTRATION IN A STREAM MAY BE REPRESENTED BY THE EQUATION

$$\frac{DC}{DT} = K(C_s - C) + (P-R)$$

WHERE

C = CONCENTRATION
C_s = SATURATION CONCENTRATION
K = RESPIRATION COEFFICIENT
P = GROSS PRODUCTION
R = WRESC PRODUCTION MAY BE REPRESENTED BY A FOURIER SERIES

$$P-R = 10/2 \times \text{SUM FROM } N=1 \text{ TO } K_0 \text{ OF } (AN \cos(N \omega \pi t/2))$$

WHERE

AN = COEFFICIENTS
W = 2\pi/PERIOD OF OBSERVATION
T = TIME

THE DIFFERENTIAL EQUATION MAY BE SOLVED FOR DOWNSTREAM CONCENTRATION

$$D(J+1) = \exp(-K*\Delta T) \times U(J) + \left[1/\exp(K*T_{J+1})\right] \times \text{INTEGRAL FROM } T(J) \text{ TO } T(J+1) \text{ OF }$$

$$K \times \text{COS}(N \omega t) \times DT$$

$$+ \text{SUM FROM } N=1 \text{ TO } K_0 \text{ OF } (AN*(K*\text{COS}(N \omega T(J+1)) - (K*\text{COS}(N \omega T(J)) - (N \omega \text{SIN}(N \omega T(J+1))))$$

WHERE

D = DOWNSTREAM CONCENTRATION
U = UPSTREAM CONCENTRATION
T = TIME
DELTA = T(J+1) - T(J) = RESIDENCE TIME

SOLUTION OF THE EQUATION USING OBSERVED UPSTREAM CONCENTRATION DATA YIELDS PREDICTED DOWNSTREAM CONCENTRATIONS WHICH MAY BE COMPARED WITH OBSERVED VALUES.
READ IN ALPHANUMERIC CHARACTERS FOR LOCATION AND DATE

READ IN DATA FOR epochs

READ IN RESIDENCE TIME (HOURS)

READ IN ATOMIC PRESSURE (MILLIBARS, CORRECTED TO SEA LEVEL)

READ IN NUMBER OF DATA POINTS
READ 5, D, DT, PRE, N, K
5 FORMAT(3F15.7,2I5)

READ IN AK REAERATION COEFFICIENT (METERS/HOUR)
START-STARTING TIME (HOURS)

READ 10, AK, START
10 FORMAT(2F15.5)

INITIALIZE ARRAYS

DO 600 I = 1, N

US(I) = 0.0
DS(I) = 0.0
600 CONTINUE

READ IN OXYGEN DATA

UP, DOWNSTREAM CONCENTRATION (GRAMS/CUBIC METER)
US, DS = UP, DOWNSTREAM TEMPERATURE (DEGREES CENTIGRADE)

605 IF (KODE.EQ.4) GO TO 609
606 CONTINUE

READ IN UPSTREAM OXYGEN CONCENTRATION, TEMPERATURE, AND RADIATION

DO 800 I = 1, N

READ 600, US(I), U(I), URAD

IF (U(I) > 0.0) THEN
  IF (KODE.EQ.1) RADIEN, URAD
  IF (KODE.EQ.3) AND, KRAD, EQ.2
goto 609
  IF (KODE.EQ.4) goto 606

800 CONTINUE

READ IN DOWNSTREAM OXYGEN CONCENTRATION, TEMPERATURE, AND RADIATION

READ 6100, DS(I), D(I), DRAD

IF (D(I) > 0.0) THEN
  IF (KODE.EQ.2) RADIEN, DRAD
  IF (KODE.EQ.3) goto 2

IF RO RADIATION DATA IS AVAILABLE, READ IN TIME OF SUNRISE
AND SUNSET (HOURS)

READ 1, F1, F2
1 FORMAT(2F15.4)
155 F1 = F1 + 1.0
125 F2 = F2 + 1.0
1 DO 70 I=1,N
2 IF(NUMR.EQ.0) NUMB=1
VMIN=1000.
VMAX=0.
K=1
KODE=1
KSAY=KODE
DAY=0
DAY=DOAT(N-1)*D
N=0.28316/(2.6*DXY)
400=ST.2.001
PRINT 6000
6000 FORMAT(1H1,5CH%%%%%%%%%%%%%%%%%)
CORR=(PRES+0.19)/29.92
IF(PRES.GT.90.0) CURR=(PRES-17.01)/1013.2
619 DO 70 I=1,N
C CONVERT TEMPERATURE TO SATURATION CONCENTRATION OF OXYGEN
C US(I)=A1-A2+US(I)+3.4*US(I)*2+14*US(I)*5
DS(I)=A1-A2+DS(I)+3.4*DS(I)*2+14*DS(I)*5
C CORRECT SATURATION FOR ATMOSPHERIC PRESSURE
C US(I)=US(I)*CORR
DS(I)=DS(I)*CORR
SAV(I)=US(I)
US(I)=US(I)
US(I)=US(I)
USS(U1)=US(1)
IF(KODE.EQ.4) GO TO 61
C FIND MAXIMUM AND MINIMUM VALUES FOR CONCENTRATION
C IF(U(I),LT,VMIN) VMIN=U(I)
IF(U(I),GT,VMAX) VMAX=U(I)
IF(US(I),LT,VMAX) VMAX=US(I)
IF(KMDE.GE.3) GO TO 70
61 CONTINUE
IF(DB(I),LT,VMIN) VMIN=DS(I)
IF(DB(I),LT,VMAX) VMAX=DB(I)
IF(DB(I),LT,VMAX) VMAX=DB(I)
70 CONTINUE
C CALCULATE THE INTEGRAL OF RADIATION OVER THE INTERVAL FROM SUNRISE TO SUNSET, USING THE TRAPEZOIDAL RULE
C RINT=0.
IF(KRAD.EQ.0) GO TO 750
IF(KRAD.IEQ.HTHRS) GO TO 750
I=10000
730 I=I+1
IF(KRAD.IEQ.HTHRS) GO TO 730
IF(I1,>1) I1=1
PRINTRAD(I1)*RADIANT(1)*D*PRINT
I2=I1
GO TO 740
730 IF(I1,>2) GO TO 740
IF(RAD(I1),<=THRE) GO TO 740
740 CONTINUE
IF(I1,=0) I1=1
PRINTRAD*60.0/2.0
IF(PRINT,=0.5) KRADE
750 CONTINUE
C
PRINT HEADING
C
PRINT 1041,AK,0.0,D
1041 FORMAT(12X,15HEAPlER, COEF.**,F6.3,5X,111PARAMETERS**,12,5X,+
    *10HRES, TIME**F5.2)
    PRINT 1001,AL1,AL2,AL3,AL4,AL5
1001 FORMAT(14.5A10)
    PRINT 1040
1040 FORMAT(5HRETURN,5Htwo statements in this program)
PRINT 975
975 FORMAT(1H0,2X,34HUPSTREAM DOWNSTREAM)
    IF(KRADE,=0.0) GO TO 949
PRINT 990
990 FORMAI1,3X,40H0XYGEN OXYGEN SATURATION SATURATION RADIATION TIME)
    GO TO 949
949 PRINT 995
995 FORMAT(1H3X,50HBeAT BeAT ProducLivity—Two Station Method)
    IF(XMFRF=0.5) PRINT 1070
1070 FORMAT(14.3HNET PRODUCTIVITY—TWO STATION METHOD)
    IF(KODE,=0.3) PRINT 1080
1080 FORMAT(14.14HNET PRODUCTIVITY—SINGLE STATION (UPSTREAM))

A6
IF (MUF1.EQ.4) PRINT 1090
1090 FORMAT (1H1,14HNET PRODUCTIVITY-SINGLE STATION(DOWNSTREAM))
   PRINT 1040
   PRINT 5001, AL1, AL2, AL3, AL4, AL5
   PRINT 1080
   PRINT 1100
1100 FORMAT (1I0,2X,38HDELTA NV, VALS, DAT/Delta REAL PRFES.)
   MIXN=1+1
   PRINT 1110, D, NV N A, PRES
1110 FORMAT (1I1, 1F5.1, 5X, 1.7X, 12.5X, F5.2, 7X, 2, F8.2)
300 IF (KODE.EQ.3) GO TO 310
   IF (KODE.EQ.4) GO TO 320
   NC / 1 = 1:
   DO (1=DN 1, 1=M-1)
   71 NS(I)=NS(I-1)+1
   GO TO 350
310 DO 315 IT=1, N
   DO (1=DN 1, 1=M-1)
   315 NS(I)=NS(I-1)+1
   GO TO 350
320 DO 325 IT=1, N
   US(I)=SAV(I)
   US(I)=NS(I)
   DO (1=DN 1, 1=M-1)
325 US(I)=NS(I-1)
C   CALCULATE PARTS OF THE EQUATION FOR DOWNSTREAM CONCENTRATIONS
C   AND STORE FOR CONVENIENCE.
350 ZM=1
   NL=M/2
   LL=0-1
   DO 700 L=1/N
   MUS(I)=AL-1,0
   DO 700 L=1, NL
   700 MUS(I)=AL-1,0
   DO 710 L=1, LL
   710 ZCOS(L1, L)*COS(S(V+1)
700 Z=H(I-AL)*S1(V+1)
   IF (KODE.EQ, 4) GO TO 2001
   MS=EXP(-A=A)
   NU 2000 I=1, A
   A=AL(NS(I)-US(I)1)*A(I-O, S)A, D
   2001 CONTINUE
C   SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
C      (PARAMETERS)
C   CALL PARAM
C PRINT VALUES OF PARAMETERS

1020 FORMAT(10D17.17HPARAMETER VALUES-)
DO 210 I=1,X0
210 FORMAT(10I10,10I)
1030 FORMAT(1H,12,2X,E15.8)
PRINT 1040
PRINT 1050
1050 FORMAT(1NG,17HPARAMETER REFERENCES)
PRINT 1060
1060 FORMAT(1H,2X,4TIME,4X,9HPREDICTED,11X,9Hobserved)

C SUBROUTINE COMPAR CALCULATES DOWNSTREAM OXYGEN CONCENTRATIONS FROM
C UPSTREAM DATA AND COMPARES CALCULATED AND OBSERVED VALUES
C
CALL COMPAR

C INTEGRATE PRODUCTION OVER THE DARK INTERVALS AND DIVIDE BY THE
C LENGTH OF THE INTERVALS TO CALCULATE MEAN RESPIRATION
C
IF(RAD(1),GT,THRES) GO TO 215
   OR=1,1N+1-1-12
   IF(GN,GE,0) OR=1
   P0 211 I=1,11
211 R=PHAN=MEAN+PROD(I)
   I=I+1
   D0 212 I=1,12
212 R=PHAN=MEAN+PROD(I)
   R=PHAN=MEAN*PROD(I)*PROD(1)*PROD(12)*PROD(I1)*2.0
   R=R=DAY-R=MEAN/DR

C CALCULATE NET AND GROSS PRODUCTION OF OXYGEN
215 PNET=DAY*Q(I)
   PPR=PR-P=MEAN
   IF(PR=PR=Q(I),1)
   IF(PR,LE,PR=Q(I),1)
   IF(PR,LE,PR=Q(I),1)
   IF(PR,LE,PR=Q(I),1)
   IF(KRAD.GE,1) GO TO 9

C PRINT PRODUCTION, RESPIRATION AND RADIATION DATA
C
PRINT 6,PNET,R=MEAN,PQDS
   FORMAT(1D0,15HNET PRODUCTION,F7.2,3X,12HRESPIRATION,F7.2,3X,17H
   ROSS PRODUCTION=F7.2,3X,27HNO RADIATION DATA AVAILABLE)
   NO IN 214
9 PRINT 213,PNET,R=MEAN,PQDS,PRINT
213 FORMAT(2H0,15HNET PRODUCTION,F7.2,3X,12HRESPIRATION,F7.2,3X,17H
   ROSS PRODUCTION=F7.2,3X,16HTOTAL RADIATION=F7.2)
IF(KODE,NE,1) GO TO 400
KODE=1
400 IF(KODE,NE,0) GO TO 6030
KODE=KODE+1
IF(KODE,GT,4) GO TO 6030
D=DT
N=N+1
M=2
N=N+1
GO TO 295
6030 KODE=KSAV
N=N+1
N=N+1
GO TO 6031
6031 JX=JX-50
IF(JX,GT,50) GO TO 6031
JX=50
CALL SUBROUTINES TO PLOT OXYGEN CONCENTRATION AND PRODUCTION DATA OVER TIME AND PRODUCTION AGAINST RADIATION
IF(KODE,NE,4) GO TO 6010
PRINT 6001,AL1,AL2,AL3,AL4,AL5
6001 FORMAT(1I1,31A10,30HUPSTREAM OXYGEN AND SATURATION)
CALL OXPLOT(N,SAV,SS,XV,DT,VMIN,VMAX,IX)
6020 CONTINUE
IF(KODE,GE,3) GO TO 6021
PRINT 6002,AL1,AL2,AL3,AL4,AL5
6002 FORMAT(1I1,31A10,32HDOWNSTREAM OXYGEN AND SATURATION)
CALL OXPLOT(N,SAV,SS,XV,DT,VMIN,VMAX,IX)
IF(KRAD,NE,0) CALL RADPLOT(N,PROD,RAD,START,DT)
5002 FORMAT(1I1,31A10,18HTWO STATION METHOD)
CALL PLOT(UPROD,IX,XV,DT)
IF(KSAV,GE,3) GO TO 8000
KSAV=-1
6021 IF(KODE,NE,3) GO TO 6022
PRINT 5003,AL1,AL2,AL3,AL4,AL5
5003 FORMAT(1I1,31A10,29HSINGLE STATION UPSTREAM)
7001 CALL PLOT(UPROD,IX,XV,DT)
IF(KRAD,NE,0) CALL RADPLOT(UPROD,RAD,START,DT)
IF(KSAV,GE,3) GO TO 8000
KODE=KODE+1
6022 IF(KODE,NE,4) GO TO 6023
PRINT 5004,AL1,AL2,AL3,AL4,AL5
5004 FORMAT(1I1,31A10,29HSINGLE STATION DOWNSTREAM)
7002 CALL PLOT(DPROD,IX,XV,DT)
IF(KRAD,NE,0) CALL RADPLOT(DPROD,RAD,START,DT)
GO TO 8000
6023 IF (KODE.NE.5) GO TO 6024
   PRINT 5005, AL1, AL2, AL3, AL4, AL5
5005 FORMAT (AL1, 5X, AL2, AL3, AL4, AL5)
   GO TO 7001
6024 PRINT 5005, AL1, AL2, AL3, AL4, AL5
   GO TO 7002
8000 NDONE=NDONE+1
   IF (NDONE.EQ.2) GO TO 8005
   IF (KODE.NE.10) GO TO 7090
   IF (IDN.EQ.1) GO TO 7095
7090 KODE=1
   IDN=2
7095 KSUM=0
6099 KSUM=KSUM+1
   IF (KSUM.LE.2) GO TO 8005
   IF (KSUM.EQ.10) STOP
   GO TO 9000
C
   PRINT A SUMMARY OF CALCULATIONS
C
8005 PRINT 8006, AL1, AL2, AL3, AL4, AL5
8006 FORMAT (27X, 'SUMMARY', 5X, 5X, 5X, 10, '1/1')
   GO TO 8019
8019 PRINT 8067
8067 FORMAT (1H1, 18HTC STATION METHOD)
   PRINT 8070, AK, KU, DAT
   PRINT 8070, 1H9, 10X, 11THEORETICAL, F7.2, 5X, 11PARAMETERS, 12, 5X, 13RES
   'DENCE TIME, F7.2')
   PRINT 8071, AK, KU, IP()
   8071 FORMAT (1H9, 12X, 14NET PRODUCTION, 3X, F7.2, 3X, 16GAMS OXYGEN PER CU
   BIC METER PER DAY)
   PRINT 8072, IP()
   8072 FORMAT (1H9, 15X, 12HEPHERATION, 5X, F7.2, 3X, 16GAMS OXYGEN PER CUBI
   TE PER DAY)
   PRINT 8073, IP()
   8073 FORMAT (1H9, 15X, 12GROSS PRODUCTION, 7F7.2, 3X, 16GAMS OXYGEN PER CU
   BIC METER PER DAY)
   IF (KRAIT.EQ.0) GO TO 9009
   PRINT 8074, KINT
   PRINT 8074, 1H5, 12TOTAL RADIATION, 1X, F7.2, 3X, 1HKANGONCE, 3X)
   SLOPE=PS(1, 40, 20, KINT)
   PRINT 8075, SLOPE
8075 FORMAT (1H9, 25X, 12SLOPE, 6X, F7.3, 5X, 36HRATIO OF GROSS PROD. TO 101
   AL RADI, 17)
   PRINT 8076, PROD(1)
   8076 FORMAT (1H9, 25X, 12PROD, 12, 5X, 17H(RATIO REGRESSION))
   PRINT 8077, PROD(2)
   8077 FORMAT (1H9, 25X, 12INTERCEPT, 12X, F7.3)
   PRINT 8078, PROD(3)
8078
8009 \textbf{IF}(\textit{CODE}, \textit{EQ}, 2) \textbf{GO TO} 8009
8009 \textbf{IF}(\textit{CODE}, \textit{EQ}, 1) \textbf{GO TO} 8012
8012 \textbf{IF}(\textit{CODE}, \textit{EQ}, 3) \textbf{GO TO} 8099

8012 \textbf{IF}(\textit{CODE}, \textit{EQ}, 3) \textbf{GO TO} 8099
8064 \textbf{FORMAT}(14H,28H SINGLE STATION, DOWNSTREAM)
8064 \textbf{PRINT} \textit{A0}, \textit{AK}, \textit{KN}, \textit{DM}
8064 \textbf{PRINT} \textit{B071}, \textit{WX}, \textit{IDN}, \textbf{IF}(\textit{KRA}, \textit{EQ}, 0) \textbf{GO TO} 8099
8064 \textbf{PRINT} \textit{B074}, \textit{PGN}, \textbf{SLOPE=P01(1)*60.0/PRINT}
8064 \textbf{PRINT} \textit{B075}, \textit{SLOPE}
8064 \textbf{PRINT} \textit{B076}, \textit{UPROD}, \textit{PGN}
8064 \textbf{PRINT} \textit{B077}, \textit{UPROD}, \textit{PGN}
8064 \textbf{GO TO} 8059
\textbf{END}
SUBROUTINE PAWAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS (PARAMETERS). THE COEFFICIENTS MUST BE CHOSEN TO MINIMIZE THE CUMULATIVE ERROR, EXPRESSED AS THE SUM OF SQUARED ERRORS BETWEEN OBSERVED AND CALCULATED DOWNSTREAM CONCENTRATIONS, WHEN PARTIAL DERIVATIVES OF THE ERROR WITH RESPECT TO EACH COEFFICIENT ARE FORMED AND SET EQUAL TO ZERO, A SYSTEM OF LINEAR EQUATIONS IS FOUND WHICH MAY THEN BE SOLVED TO YIELD OPTIMUM VALUES FOR THE PARAMETERS.

COMMON AK
COMMON M, DT
COMMON START, ZCOS(50,100), ZSIN(50,100), ZSI(100)
COMMON K0, T
COMMON DO(100), U(100), G(50)
COMMON UN, UN, UN, UN, UN
COMM/AL, AL, AL, AL, AL, AL
DIMENSION N(100)
DIMENSION H(50,50), GAM(100,50), A(100), C(50)
DIMENSION T(L5,50), EX(50)
CHARACTER*10 AL, AL, AL, AL, AL

COMMON PARTS A, R1 AND GAM FOR CONVENIENCE.

DO 10 I=1, N
10 A(I)=COS(I)*SIN(I)

DO 20 J=1, N
20 GAM(J,1)=0.0

DO 30 K=1, 10
30 IS=2*K

V=IS-1
LO=AL-1

W1=1.0*(AK+2+V+V)**2

W2=AK-ZCOS(I)*LO+V+V+ZSIN(I)*LO-5*(AK-ZCOS(I)*V)+V

I=ZSIN(I)*V)

20 GAM(I,IS)=W1+W2

SET UP MATRICES A AND GAM TO CONTAIN THE LINEAR SYSTEM FOUND FROM MINIMIZING THE ERROR, SUCH THAT A=CG (WHERE MATRIX A CONTAINS THE PARAMETERS).

DO 40 I=1, N
40 DO J=1, N

R(I,J)=R(I,J)*GAM(L,J)*GAM(L,I)

R(I,1)=R(I,1)*S)/(2.0*AK)

R(I,1)=B1*E
CALL SUBROUTINES TO SOLVE THE SYSTEM OF LINEAR EQUATIONS BY GAUSSIAN ELIMINATION. IF A SINGULAR MATRIX IS FOUND, STOP EXECUTION.

DO 46 J=1,K0
C(J)=0.
R(1,1)=D
DO 39 I=1,N
R(I,1)=R(I,1)+B(1,1)*BAM(I,1)
35 R(I,1)=R(I,1)*BAM(I,1)*DO(L)-A(L))
40 R(I,1)=R(I,1)*BAM(I,1)
C(1)=0.0
DO 69 I=1,N
60 C(I)=C(I)+DO(L)-A(L)

CALL DECOMP(K0,BUL,KS)
IF(KS,GT.0,1) STOP
CALL SOLVE(K0,BUL,C+GK)

STORE OPTIMUM VALUES FOR THE PARAMETERS IN G.

DO 400 J=1,K0
400 G(J)=G(J)/2.0
RETURN
END
SUBROUTINE CONMPAR

SUBROUTINE COMPAR CALCULATES PREDICTED CONCENTRATIONS USING THE
EQUATION FOR DOWNSTREAM CONCENTRATION. ERROR IN CALCULATION IS
EXPRESSED AS THE SUM OF SQUARED ERRORS BETWEEN OBSERVED AND
CALCULATED DOWNSTREAM CONCENTRATIONS.

COMMON AK
COMMON N,D,T
COMMON STAR, ZCS(50,100), ZSin(50,100), CSI(100)
COMMON K, Z
COMMON D0(100), U(100), GI(50)
COMMON D, N, W, D1, S, K
COMMON AL, AL1, AL2, AL3, AL4, AL5, KONE
COMMON PR, PROD(100), DPROD(100), DPROD(100)
DIFUSION C(50)
CHARACTER*10 AL1, AL2, AL3, AL4, AL5
DO 402 J=1, K0
422 C(j) = D(j)
K = 0

CALCULATE AND STORE PARTS OF THE EQUATION

DO 90 L=1, N

L0=L+1
AL = 1

T1 = T1 + D2
V1 = V1 + D1

R2 = 0

DO 90 LS=2, K0

V = V1

V = V1 + 1


T1 = T1 + D2

PRINT CONCENTRATION AND TIME

GO TO 98

PRINT TIME AND CALCULATED AND OBSERVED VALUES

PRINT 1070, TIME, R, P
1070 FORMAT(1X, 6.2, 3X, E14.7, 8X, E14.7)
GO TO 90

GO TO 89

GO TO 98
CALCULATE AND PRINT SUM OF SQUARED ERRORS

CALCULATE AND PRINT GROSS PRODUCTION
SUBROUTINE DECOMP(MN, A, UL, KS)

SUBROUTINE DECOMP PERFORMS A TRIANGULAR DECOMPOSITION OF MATRIX

A * AX = B, DIVIDING IT INTO AN UPPER AND LOWER TRIANGULAR MATRIX, THE SYSTEM

AX = B MAY THEN BE WRITTEN LUX = B, WHICH IS SOLVED IN SUBROUTINE

C

DIMENSION A(MN, MN), UL(MN, MN), SCALE(MN), IPS(MN)
COMMON /E0/ IPS

MEIN

K = 0
DO 10 I = 1, MN
IPS(I) = 0, ROWIPS(I) = 0
IU(I) = J(I)
IJP = A(I, J(I))
1 ROWIPS(I) = ROWIPS(I) + 1, J(I) = I,
10 CONTINUE

IF (ROWIPS(I) = A(I, J(I))) 1, 2, 2
1 ROWIPS(I) = A(I, J(I))
2 CONTINUE

IF (ROWIPS(I) = 3, 4, 3)
3 SCALPS(I) = 2.0 / ROWIPS(I)
4 GO TO 5

CALL SING(I)

K = 1

SCALPS(I) = 0.0
5 CONTINUE

MEIN = 1
DO 17 K = 1, MN
KMP = 1
11 MEIN = 1
17 CONTINUE

IF (MEIN = 11, 12, 13)
12 CALL SING(I)

KS = 2
GO TO 17

13 IF (K = 14, 15, 14)

14 IF (K = 1, 15, 14)

15 IF (I = 16, I = 1)

16 CONTINUE

17 CONTINUE

KS = 2
18 CONTINUE

END
SUBROUTINE SOLVE(INX,UL,B,X)

C THIS SUBROUTINE SOLVES THE TWO SYSTEMS L*Y = A AND U*X = Y TO FIND
C MATRIX X.

DIMENSION UL(50,50),A(50),X(50),IP550)
COMMON/TPS/ N,NN
N=1
IP=IP51)
X(1)*=R(IP)

C FORWARD ELIMINATION

DO 2 I=2,N
1 IP=IP5(I)
2 X(I)*=R(IP)
SUM=0.0
DO 3 J=1,I-1
3 SUM=SUM+UL(IP,J)*X(J)
2 X(I)*=R(IP)-SUM
1 IP=IP5(N)
X(N)*=X(N)/UL(IP,N)
RETURN
END

SUBROUTINE SING(INX)

C THIS SUBROUTINE PRINTS DIAGNOSTICS IF A SINGULAR MATRIX IS
C FOUND IN DECOMP.

IF(INX,E0.2) GO TO 2
PRINT 11
11 FORMAT(1HO,33CMATRIX WITH ZERO ROW IN DECOMPOSE)
RETURN
2 PRINT 12
12 FORMAT(1HO,51HSINGULAR MATRIX IN DECOMPOSE, ZERO DIVIDE IN SOLVE.)
RETURN
END
SUBROUTINE PLOT(MPT,VAL,IX,XVAL,CX)

THIS SUBROUTINE PLOTS OXYGEN PRODUCTION AGAINST TIME.

COMMON AK
COMMON MDT
COMMON START,2COS(90,100),2SIN(90,100),CST(100)
COMMON/MPT/PM5,VMAX,VMIN
DIMENSION VaL(MPT),CLEAN(3),LINE(101)
INTEGER C,EA,INP,DOT,BLANK,STAR
DATA NOT,BLANK,STAR/",","",""/
DATA P(1)/1/1/
TSAX=CX

CPL0T(PLOT,Y
XVAL=6,CHPLOT
VMAX=-1000
VMIN=1000.

CALCULATE MAXIMUM AND MINIMUM PRODUCTION VALUES

DO 50 IX=MPT,IX
IF(VMAX.GT.VMAX) VMAX=VAL(I)
IF(VMIN.LT.VMIN) VMIN=VAL(I)
50 CONTINUE

PRINT TITLE

100 PRINT 100

PRINT 100 FORMA7(HO,25X,54HNET PRODUCTIVITY,GRAMS OXYGEN PER CUBIC METER PE
HR HOUR)

KPL=2

SCALE AND PRINT PRODUCTION AXIS

IF(VMAX.LT.1.5,ANV,VMIN.GT.-1.0) GO TO 60
VMAX=2.0
VMIN=-3.0

PRINT 100

100 FORMA7(12H,15X,4H-2.0,14X,4H-1.0,16X,3H0,0,16X,3H1,0,17X,3H2,0, 117X,3H3,0)

GO TO 70

60 KPL=3

PRINT 100

100 FORMAT7(15X,4H-1.0,14X,4H0,5,16X,3H0,0,16X,3H0,9,17X,3H1,0, 117X,3H1,5)

70 DO 101 J=1,101
LINE(J)*=N0

101 FORMA7(12H,15X,4H-1.0,14X,4H-1,0,16X,3H0,0,16X,3H1,0,17X,3H2,0, 117X,3H3,0)

IF(Y,EQ,0) LINE(J)*=STAR
110 CONTINUE
PRINT 535,LINE
113 FORMAT(3x,101X)
DO 114 J=-1,10
111 LINE(J)=BLANK
LINE(41)=DOT
Z=0.
C
STORE PRODUCTION VALUE FOR EACH TIME
C
DO 116 K=1,4P+1
XVALC=XVALC+CPLT
IF(VAL(K),RT,VMAX) VAL(K)=VMAX
IF(VAL(K),LT,VMIN) VAL(K)=VMIN
J=GR(N,66*K-1)*(1)+1+S
IF(KPL,60,2) J=100.0*(1.6/VMAX)*VAL(K)+8.4+1.5
IF(J,Eq,41) Z=10.
LINE(J)=P(1)
CLEAN(1)=0
IF(AMS(XVAL-XVALC,Gt,0.001) GO TO 113
XFACT=XFACT+1.0
IF(X.X,Em,0.1 LINE(41)=STAR
Z=0.
XVAL=CE0.
XFACT*XVAL*START
60 IF(X,GT,24.0) GO TO 90
IF(XVAL/LT,1.1) GO TO 81
C
C PRINT POINTS
C
PRINT 119,X,LIN
104 FORMAT(4X,F9.0,6H00 HRS,101X)
GO TO 112
81 PRINT 105,X,LIN
119 FORMAT(4X,F9.2,3X,3H000,HRS,1X,101X)
GO TO 114
90 X2=X+24.0
GO TO 60
113 PRINT 103,LIN
114 ICLEAN=CLEAN(1)
LINE(ICLEAN)=BLANK
LINE(41)=DOT
116 CONTINUE
CPLT=TSAV
CONTINUE
RETURN
END
A19
SUBROUTINE OXYPLOT(X,Y1,X2,YVAL,CPLOT,VMIN,VMAX,IX)

C THIS SUBROUTINE PLTS OXYGEN CONCENTRATION AGAINST TIME

COMMON AK
COMMON M,D,T

COMMON START,ZCOS(50,100),ZSIN(50,100),CSI(100)

DIMENSION X(HMT),X2(HMT),CLEAN(2),LINE(10),P(21,V<5)

INTEGER CLEAN,LINE,P,DOT,BLANK,STAR

DATA DOT,ANX,STAR/1H,1H,1H/

DATA P(11,P(5)*3O,1H)/

CHARACTER*1 JRJ

EQUIVALENCE(JRJ,IDENT)

JRJ=1

SCALE CONCENTRATION AXIS

DY=(VMAX-VMIN)/5.0

DO 11 I=1,6

11 Y(I)=Y(I-1)+DY

PRINT 100,YMIN,VMAX

100 FORMAT(1H0,35X,42HOXYGEN CONCENTRATION,GRAMS PER CUBIC METER)

PRINT CONCENTRATION AXIS

PRINT 101,Y11,Y(1),Y(2),Y(3),Y(4),Y(5),Y(6)

101 FORMAT(12X,6(F5.1,S15X))

DO 110 J=1,101

LINE(J)=0

110 CONTINUE

PRINT 133,LINE

PRINT 333,LINE

CONTINUE

A20
STORE CONCENTRATION VALUES FOR EACH TIME

DO 116 K=1, MPT, 1
XVALC=XVALC+CPLOT
J=(100,0)/(VMAX-VMIN)*(X1(K)-VMIN)*1.5
LINE(J)=IDEN
CLEAN(J)=0
J=(100,0)/(VMAX-VMIN)*(X2(K)-VMIN)*1.5
LINE(J)=P(2)
CLEAN(2)=J
IF(ABS(XVALC-XVAL).GT.0,001) GO TO 113
XFACT=XFACT,.0
LINE(I)=STAR
XVALC=0
XFACT=XVALC=STAR
80 IF(X.GT.24.0) GO TO 90
IF(XVALC.LT.1) GO TO 81

PRINT CONCENTRATION VALUES

104 PRINT 104,X,L,J
FORMAT(3X,2F9.5,2X,SHRS,IX,101A1)
GO TO 114
81 PRINT 105,X,L,J
FORMAT(3X,2F9.5,2X,SHRS,IX,101A1)
GO TO 114
90 X=X-24.0
GO TO 80
113 PRINT 103,X,L
114 DO 115 I=1,2
ICLEAN=CLEAN(I)
LINE(ICLEAN)=BLANK
115 CONTINUE
LINE(1)=DOT
116 CONTINUE
VMINS=VMINS
VMAX=VMAXS
CPLOT=TSAV
RETURN
END
SUBROUTINE RADPLT(N,M,R,START,DT)
C
THIS SUBROUTINE PLOTS NET PRODUCTIVITY AGAINST RADIATION.

COMMON/N,T/N
DIMENSION $S(*)$,
DIMENSION P(*)

INTEGER N

DATA Y/10X/
DATA T(1),T(2),T(3),T(4),T(5),T(6),T(7),T(8),T(9),T(10),T(11),T(12),T(13),T(14),T(15),T(16),T(17),T(18),T(19),T(20),X/10X,

IWIN=(6.0-START)/0.1+1
IMAX=(20.0-START)/0.1+1
IS=1

CALCULATE MAXIMUM VALUES FOR PRODUCTION AND RADIATION.

RMAX=1000,
PMAX=1000,

DO 10 I=1,N
IF(R(I),GT,RMAX) RMAX=R(I)
IF(P(I),GT,PMAX) PMAX=P(I)
10 CONTINUE

IF(RMAX.LE.5) DX=0.01
IF(RMAX.GT.5.0) DX=0.02
IF(PMAX.LE.2.0) DX=0.04
IF(PMAX.GT.2.0) DX=0.08

KVAL=3.0*DX
KVAL=DX

PRINT TITLES
C

PRINT 105
105 FORMAT(1H1,33H NET PRODUCTIVITY VERSUS RADIATION)
PRINT 106
106 FORMAT(1H1,33H NET PRODUCTIVITY, GRAMS OXYGEN PER CUBIC METER PER HOUR)

SCALE PRODUCTION AXIS
C

Y(1)=INT(10.0*ARG(PMIN)*1.0)
Y(15)=YP(15)/10.0
PMAX=P(YP(1))

PMAX=P(YP(1))
HY=(PHAX-YP(I))/5.0
DU 15 I=2,6
15 YP(I)=YP(I-1)*HY
PRINT PRODUCTION AXIS
PRINT 103,YP(1),YP(2),YP(3),YP(4),YP(5),YP(6)
FORMAT(2X,L9.4,F15.5)
DO 20 J=1,101
LINE(J)=DOT
M=M+60D0,J=1,20
IF(MM.EQ.0)LINE(J)=STAR
20 CONTINUE
PRINT 103,LINE
FORMAT(15X,101A1)
NO 23 J=1,101
29 LINE(J)=BLANK
C CALCULATE POINTS AND STORE VALUES
DU 10G J=1,96
X=(J-1)*DX
YP=YP-JY2.0
XM=X-DX2.0
KV,LC=(Y)LC*DX
W=0
DO 50 J=1,4
IF(R(J).GE.MS)GO TO 50
IF(R(J).LT.XM,JM=J,1.GE.XP)GO TO 50
POINT(KK+1)=XP(J)
KK=KK+1
50 CONTINUE
KP=1
IF(KP.EQ.0)GO TO 75
1PS=1
55 YMIN=1000.
NO 60 K=1,
1.MapPath(I,J)=XP(I)-YMIN)GO TO 60
YP=YP(KM(J))
60 CONTINUE
POINT(I,J)=YP000.0
KK=KK+1
1PS=(500.0/YPHAX-PMIN))*YMIN-PMIN)*1.5
LINE(PP)=Y
IF(PH(J).LT.-10M+OR.PH(I).GT.-10M)GO TO 71
1TH=(FLOAT(M(I)-IMIN)*DT+1.1
1TH=(1.0/T1TH)
A23
IF (IP.EQ.IPS) LINE(IP)=0
IPS=IP
71 IF (IP.EQ.IPS) GO TO 75
GO TO 55
75 IF (XVALC.XWALC).GT.0.000001 GO TO 90
XLACT=XLACT+1.0
LINE(IP)=1
XVALC=0.
XLACT=XLACT+1.0
201 FORMAT(1H+,97X,14HA-0800 TO 1659)
202 FORMAT(1H+,97X,14HA-0700 TO 0759)
203 FORMAT(1H+,97X,14HA-0600 TO 0649)
204 FORMAT(1H+,97X,14HA-0500 TO 0559)
205 FORMAT(1H+,97X,14HE-1000 TO 1059)
206 FORMAT(1H+,97X,14HF-1100 TO 1159)
207 FORMAT(1H+,97X,14HC-1200 TO 1259)
208 FORMAT(1H+,97X,14HH-1300 TO 1359)
209 FORMAT(1H+,97X,14HI-1400 TO 1459)
210 FORMAT(1H+,97X,14HJ-1500 TO 1559)
211 FORMAT(1H+,97X,14HK-1600 TO 1659)
212 FORMAT(1H+,97X,14HL-1700 TO 1759)
213 FORMAT(1H+,97X,14HM-1800 TO 1859)
214 FORMAT(1H+,97X,14HN-1900 TO 1959)
215 FORMAT(1H+,97X,14HO-2000 TO 2059)
216 FORMAT(1H+,97X,14Hp-COINCIDING POINTS)
"PRINT RADIATION AXIS AND POINTS"
C
C
C
C
C
C
204 FORMAT(3X,FR,2,1X,3HLYS,3X,1011)
205 PRINT 203
206 PRINT 206
207 PRINT 209
208 PRINT 212
209 PRINT 215
GO TO 95
90 PRINT 103,111
91 IF (J.GT.2) PRINT 201
92 IF (J.GT.3) PRINT 202
93 IF (J.GT.5) PRINT 204
94 IF (J.GT.6) PRINT 205
95 IF (J.GT.8) PRINT 207
96 IF (J.GT.9) PRINT 208
97 IF (J.GT.11) PRINT 210
98 IF (J.GT.12) PRINT 211
99 IF (J.GT.14) PRINT 213
100 IF (J.GT.15) PRINT 214
101 CONTINUE
C. CALCULATE AND PRINT SLOPE, INTERCEPT AND CORRELATION COEFFICIENT.

DO 1050 I=1,1,N
  SUMX=SUMX+X(I)
  SUMY=SUMY+Y(I)
  SUM=SUM+X(I)**2
  SUMXY=SUMXY+Y(I)*X(I)
1050 CONTINUE

R=SQR(1/(N-1)*SUM)

A=(SUMXY-1 SUMX SUMY)/(SUM*SUMY SUMX**2 SUMY**2)

B=(SUM+SUMXY SUMX SUMY)/(SUM+SUMXY SUMX**2 SUMY**2)

PRINT 150, A, B, R

150 FORMAT(1H5, 10HINTERCEPT = , F7.3, 3X, SLOPE = , F7.4, 3X, 24HCorrelation C

Efficiency = , F8.3)

RETURN

END
<table>
<thead>
<tr>
<th>FORTRAN Identifier</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALL, AL2, AL3, AL4, AL5</td>
<td>Alphanumeric problem identifiers (e.g. date)</td>
</tr>
<tr>
<td>AK</td>
<td>Reaeration coefficient</td>
</tr>
<tr>
<td>D</td>
<td>Residence time</td>
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<tr>
<td>DO</td>
<td>Downstream oxygen concentrations</td>
</tr>
<tr>
<td>DRAD</td>
<td>Downstream radiation</td>
</tr>
<tr>
<td>DS</td>
<td>Downstream temperature</td>
</tr>
<tr>
<td>DT</td>
<td>Data sampling interval</td>
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<tr>
<td>F1</td>
<td>Time of sunrise</td>
</tr>
<tr>
<td>F2</td>
<td>Time of sunset</td>
</tr>
<tr>
<td>KO</td>
<td>Number of Fourier coefficients</td>
</tr>
<tr>
<td>KRAD</td>
<td>Code for radiation = 0 if no data are available, = 1 if radiation is measured at the upstream station, = 2 if radiation is measured at the downstream station</td>
</tr>
<tr>
<td>KODE</td>
<td>Operation code = 2 for two station method, = 3 for single station upstream, = 4 for single station downstream, = 1 for all of the above</td>
</tr>
<tr>
<td>N</td>
<td>Number of data points</td>
</tr>
<tr>
<td>NUMB</td>
<td>Number of days of data to process</td>
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<tr>
<td>PRES</td>
<td>Atmospheric pressure in millibars corrected to sea level</td>
</tr>
<tr>
<td>START</td>
<td>Starting time</td>
</tr>
<tr>
<td>THRS</td>
<td>Threshold value of radiation below which radiation is considered zero</td>
</tr>
<tr>
<td>U</td>
<td>Upstream oxygen concentrations</td>
</tr>
<tr>
<td>URAD</td>
<td>Upstream radiation</td>
</tr>
<tr>
<td>US</td>
<td>Upstream temperature</td>
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### Table A2

**Cards For Input to Flowing Water Program**

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<tr>
<th>Card Number</th>
<th>Variables</th>
<th>Format</th>
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<td>1</td>
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<td>2</td>
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<td>3</td>
<td>KODE, KRAD, THRS</td>
<td>212,F10</td>
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<td>4</td>
<td>D, DT, PRBS, N, KO</td>
<td>3F10,2I5</td>
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<tr>
<td>5</td>
<td>AK, START</td>
<td>2F10</td>
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<tr>
<td>6 through N+5</td>
<td>US(I), U(I), URAD(I)</td>
<td>Free field</td>
</tr>
<tr>
<td>N+5 through 2N+5</td>
<td>DS(I), DO(I), DRAD(I)</td>
<td>Free field</td>
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<tr>
<td>2N+6</td>
<td>F1, F2</td>
<td>2F10</td>
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26 JULY 1973 MEASURED
DOWNSTREAM OXYGEN AND SATURATION

<table>
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<th>8:00</th>
<th>8:10</th>
<th>8:20</th>
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</table>

Figure A1. Typical output from flowing water program (sheet 1 of 3)
Figure Al. (sheet 3 of 3)
APPENDIX B: STANDING WATER, DEPTH AVERAGE PROGRAM

Input

1. Definitions of the FORTRAN variables are given in Tables A1 and B1 and the order in which the cards are read and the appropriate formats are given in Table B2. The first card (NUMB) is required only before the initial day of data and the last card (F1,F2) is required only if radiation data are not available.

Listing

2. A listing of the computer program follows.

Output

3. The output from this program is similar to the output from the flowing water program (Appendix A). Figure B1 shows examples of the line printer plots.

4. Subroutines DECOMP, SOLVE, SING and RADPLT are also part of this program. Listings of these subroutines are given in Appendix A.
THIS PROGRAM CALCULATES RATES OF PHOTOSYNTHESIS AND RESPIRATION

IN A RIVER COMMUNITY USING A METHOD DEVELOPED BY MAHON G. KELLY,


METHOD

MODIFICATION FOR STANDING WATER-AVERAGE OXYGEN BUDGET.

THE MASS BALANCE EQUATION FOR OXYGEN IN STANDING WATER MAY BE REPRESENTED BY THE EQUATION

\[ \frac{dc_{\text{ave}}}{dt} = K(C_s - C_{\text{surf}})(P-R) \]

WHERE \( C_{\text{ave}} \) = AVERAGE CONCENTRATION (ENTIRE WATER BODY)

\( C_s \) = SATURATION CONCENTRATION (SURFACE)

\( C_{\text{surf}} \) = SURFACE CONCENTRATION

\( k \) = REAERATION COEFFICIENT

\( P-R \) = NET PRODUCTIVITY

NET PRODUCTIVITY MAY BE REPRESENTED BY A FOURIER SERIES

\[ P-R = \sum_{n=1}^{K} A_n \cos(n\pi T) \]

WHERE \( A_n \) = COEFFICIENTS

\( \pi \) = PERIOD OF OBSERVATION

\( T \) = TIME

THE DIFFERENTIAL EQUATION MAY BE SOLVED USING KNOWN SURFACE VALUES AND THE PREDICTED VALUES OF \( C_{\text{ave}} \) MAY BE COMPARED WITH OBSERVED VALUES.

COMMON/AL1,AL2,AL3,AL4,AL5
COMMON/AL1,AL2,AL3,AL4,AL5
COMMON/AL1,AL2,AL3,AL4,AL5
COMMON/AY,START,YSI,SN(100,100),UI(100),OR(100),OR(100),CR(100),CT(100),TM(100)
COMMON/CR(100),C (100),CS(100),C (100),CS(100),CT(100)
COMMON/CR(100),CS(100),CT(100)
COMMON/CR(100),CS(100),CT(100)
COMMON/CR(100),CS(100),CT(100)
DIMENSION RA(100),RA(100),TM(100)
DIMENSION CR(100),CR(100),TM(100)
DIMENSION CR(100),CR(100),TM(100)
REAL SN(100),CR(100),CR(100),TM(100)
CHARACTER AL1,AL2,AL3,AL4,AL5

READ IN NUMBER OF DAYS TO RUN

READ 19,NUMB
19 FORMAT(1Z)
  NCXK=0

READ IN ALPHANUMERIC CHARACTERS FOR LOCATION AND DATE

9000 READ 2000,AL1,AL2,AL3,AL4,AL5

5000 FORMAT(9A10)

READ IN DATA MODE INFORMATION

KRAD=0 NO RADIATION DATA AVAILABLE
   =1 RADIATION MEASURED

THR=THRESHOLD VALUE OF RADIATION

READ 20, KRAD, THR
20 FORMAT(IZ,F10.0)

READ IN SALINITY (MILLIGRAMS/LITER CL)
DT=DATA INTERVAL (HOURS)

PRES=ATMOSPHERIC PRESSURE (MILLIBARS; CORRECTED TO SEA LEVEL)

N=NUMBER OF DATA POINTS
KG=NUMBER OF PARAMETERS

READ 5, SAL, DT, PRES, N, KG
5 FORMAT(16.2F10.0,5F9.0)

READ IN AK=REFRECTION COEFFICIENT (METERS/HOUR)
START=STARTING TIME (HOURS)

READ 10, AK, START
10 FORMAT(2F10.1)

READ IN DEPTH (METERS)

READ 910, DEPTH
910 FORMAT(5F2)

INITIALIZE ARRAYS

NO 600 IN=1, N
TIM(I)=0.0
GAUG(I)=0.0
CSHR(I)=0.0
TEMP(I)=0.0
400 PAH(I)=0.0

IF(KRAD.GT.0) GO TO 605

READ IN OXYGEN DATA

TIM=TIME (HOURS)

B3
CAVG = AVERAGE CONCENTRATION (GRAMS/CUBIC METER)
CSURF = SURFACE CONCENTRATION (GRAMS/CUBIC METER)
TERM = SURFACE TEMPERATURE (DEGREES CENTIGRADE)
RAD = RADIATION (LANGEYRS)

610 FORMAT (V)
   M2
611 FORMA(6100,TIM(I),CAVG(I),CSURF(I),TERM(I)
   GO TO 3
615 NO M3 = 1, N
606 READ 6100,TIM(I),CAVG(I),CSURF(I),TERM(I),RAD(I)
3 IF ( M2.NE.0 ) GO TO 2
C IF NO RADIATION DATA IS AVAILABLE, READ IN TIME OF SUNRISE
C AND SUNSET (HOURS)
C
READ 1,F1,F2
1 FORMAT (2F10.4)
   I+F1/DT+1.0
   I+F1/DT+2.0
2 W = W+F1*(1.0/2.0*DAY)
   VMIN = VMIN
   VMAX = VMAX
   NO M = 1, N
   IF (CAVG(I),T,VMIN,VMAX) VMIN = CAVG(I)
   IF (CAVG(I),T,VMAX) VMAX = CAVG(I)
912 IF (USS(I),GT,VMAX) VMAX = CS(I)
PRINT 600C
600 FORMAT (14,15H

CONVET TEMPERATURE TO SATURATION CONCENTRATION OF OXYGEN

619 NO 76 I = 1, N
   CALL SATURAT(CS(I),TERM(I),SAL)
C
C CORRECT SATURATION FOR ATMOSPHERIC PRESSURE
C
CS(I) = CS(I)*CORR

C CALCULATE THE INTEGRAL OF RADIATION OVER THE INTERVAL FROM SUNRISE
to SUNSET, USING THE TRAPEZOIDAL RULE
C
RIMT = 0
   IF (RAD(I),TIM,THRS) GO TO 750
   IF (RAD,END,0) GO TO 750
   TIM = TIM
   IN 74C = 1, N
GO TO 949
949 DO 990 I=1,N
IF(KRAD NE 0) GO TO 950
PRINT 1005,TIM(I),CAVG(I),CSURF(I),CS(I)
1005 FORMAT(1H,5F15.4)
GO TO 950
950 PRINT 1006,TIM(I),CAVG(I),CSURF(I),CS(I),RAD(I)
1006 FORMAT(1H,5F15.4)
990 CONTINUE
C
C PRINT HEADINGS
C
PRINT 1070
1070 FORMAT(1H,11X,12HNET PRODUCTIVITY)
PRINT 1080
PRINT 5001,AL1,AL2,AL3,AL4,AL5
PRINT 1090
PRINT 1100
C CALCULATE PARTS OF THE EQUATION FOR DOWNSTREAM CONCENTRATIONS AND STORE FOR CONVENIENCE.

DO 901 I=1,K0
DO 901 J=1,N
901 Y(I,J)=(I*N+1)X(J)
DO 902 I=1,N
902 SH sharply(1)=CSURF(1)
DO 904 J=1,N
UI(J)=0.0
904 CI(J)=IC(J)+(SH(J)+CSURF(1))X(TIM(I)-TIM(I-1))/2.0
DO 905 J=1,N
905 UI(J)=UI(J)*AK/DEPTH

C SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
C (PARAMETERS)

CALL PARAM

C PRINT VALUES OF PARAMETERS

PRINT 1000
1000 FORMAT(1H0,17HPARAMETER VALUES=)
DO 210 I=1,K0
210 PRINT 1030*I,SH(I)
1030 FORMAT(1H12,2X,15.8)
PRINT 1040
1040 FORMAT(1H0,17HDOWNSTREAM OXYGEN)
PRINT 1050
1050 FORMAT(1H12,4X,4HTIME,4X,9HPREDICTED,11X,4H OBSERVED)

C SUBROUTINE COMPARE CALCULATES DOWNSTREAM OXYGEN CONCENTRATIONS FROM UPSTREAM DATA AND COMPARES CALCULATED AND OBSERVED VALUES

CALL COMPARE

C INTEGRATE PRODUCTION OVER THE DARK INTERVALS AND DIVIDE BY THE LENGTH OF THE INTERVALS TO CALCULATE MEAN RESPIRATION

IF(KRAD.GT.0.0) T1=TIM(I1)/DT+1.0
TF=IF(KRAD.GT.0.0) T2=TIM(I2)/DT+1.0
RMF=0.0

OR=1+K*Y-2
IF(YM.GT.0.0) OR=1
NC 211 I=1,N
211 RMF=RMF+OR*PROD(I)
I

B7

CALCULATE NET AND GROSS PRODUCTION OF OXYGEN

PMAYNET=PMAYNET+PMAYNET
PMAYNET=PMAYNET-PMAYNET
PMAYNET=PMAYNET/2.0

PRINT PRODUCTION, RESPIRATION AND RADIATION DATA

PRINT PMAYNET, RMEAN, PMGROS

FORMAT(4H0, 19HNET PRODUCTION=, F7.2, 3X, 12HRESPIRATION=, F7.2, 3X, 17H
+ROSS PRODUCTION=, F7.2, 3X, 27HNG RADIATION DATA AVAILABLE)
GO TO 214

PRINT PMAYNET, RMEAN, PMGROS, PMIINT

FORMAT(4H0, 19HNET PRODUCTION=, F7.2, 3X, 12HRESPIRATION=, F7.2, 3X, 17H
+ROSS PRODUCTION=, F7.2, 3X, 16H TOTAL RADIATION=, F7.2)

N=0

N=M+N

IF (PMIINT, GT, 0.) GO TO 6031

V=4.0

CALL INTERPOLATION ROUTINE TO ESTIMATE REGULARLY SPACED VALUES

CALL INTERP(XAVG, N, TIM, KT, DT, VATT)
CALL INTERP(XCS, N, TIM, KT, DT, VATT)
CALL INTERP(KRAD, N, TIM, KT, DT, VATT)

CALL SUBROUTINES TO PLOT OXYGEN CONCENTRATION AND PRODUCTION DATA OVER TIME AND PRODUCTION AGAINST RADIATION

PRINT 6001, A1, ALP, A2, A3, A4, A5

6001 FORMAT(4H0, 45HINTERPOLATED VALUES FOR OXYGEN AND SATURATION)

CALL OXYPLT(KT, CAVG, CS, KT, DM, VMIN, VMAX, DX)

PRINT 7001, A1, A2, A3, A4, A5

7002 FORMAT(4H0, 45HINTERPOLATED VALUES FOR OXYGEN AND SATURATION)

CALL OXYPLT(KT, OPMY, KT, DM, VMIN, VMAX, DX)

PRINT A SUMMARY OF CALCULATIONS
C

8005 PRINT 8066,AL1,AL2,AL3,AL4,AL5
8066 FORMAT(1H1,2H**** SUMMARY ****,5X,25X,10///)

PRINT 8067,AK,KO
8070 FORMAT(1H,12HRESPIRATION-,F5.2,5X,11HPARAMETERS-,12X)
PRINT R071,PNET
8071 FORMAT(1H6,25X,14HNET PRODUCTION-,3X,F7.2,3X,36HGRAMS OXYGEN PER BU-
+RIC METER PER DAY)
PRINT R072,RPEAN
8072 FORMAT(1H ,5X,F7.2,3X,36HGRAMS OXYGEN PER CUBI-
+6 HEAT PER DAY)
PRINT R073,PGROS
8073 FORMAT(1H ,25X,17HGR gross PRODUCTION-,F7.273X,36HGRAMS OXYGEN PER BU-
+RIC METER PER DAY)
IF(KRAD.EQ.0) GO TO 8099
PRINT 8074,RINT
8074 FORMAT(1H ,25X,16HTOTAL RADIATION-,1X,F7.2,3X,8HLANGLEYS)
SLOPE=PGROS*60.0/RINT
PRINT 8075,SLOPE
8075 FORMAT(1H0,25X,6HSLOPE-,6X,F7.3,5X,36HRATIO OF GR gross PROD. TO TOT-
+AL RAN,17)
PRINT 8076,QPROD(1)
8076 FORMAT(1H ,37X,F7.3,5X,17HFROM REGRESSION))
PRINT 8077,QPROD(2)
8077 FORMAT(1H ,25X,10HINTERCEPT-,2X,F7.3)
PRINT 8078,QPROD(3)
8078 FORMAT(1H ,25X,12HCORRELATION-,F7.3,10///)
GO TO 8099
END
SUBROUTINE SATURVITES(T,S)

C
C THIS SUBROUTINE CALCULATES THE SATURATION CONCENTRATION OF
C OXYGEN FROM TEMPERATURE AND SALINITY VALUES
C
DATA A1,A2, A3,A4,A5,A6/4,589,0,392503,6.34716E-03,1.42111E-04,
+1.77366E-05,1.65321E-07/
DATA B1,B2,B3,B4,B5,B6/13.2931,-3.70225,1.0166E-02,-2.44128E-04,
+3.60966E-06,-2.93624E-08/
DATA C1,C2,C3,C4,C5,C6/11.3993,-2.84458,5.57228E-03,-1.76234E-05,
+-3.06793E-06,7.71973E-08/
S0=A1-A2*(A3+B3*(B4+B5+B6))+(A5*A6)*T
S1=A1-A2*(A3+B3*(B4+B5+B6))+(A5*A6)*T
S2=C1-C2*(C3+C4+C5+C6)+C7
T(S=14.46) 10,10,15
T(S=30.8) (S/14.46)
RETURN
CS=S2-(S2-S1)*(S-14.46)/34.3
RETURN
END
SUBROUTINE PARAM

SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
(PARAMETERS). THE COEFFICIENTS MUST BE CHOSEN TO MINIMIZE THE
CUMULATIVE ERROR, EXPRESSED AS THE SUM OF SQUARED ERRORS BETWEEN
OBSERVED AND CALCULATED DOWNSTREAM CONCENTRATIONS, WHEN PARTIAL
DERIVATIVES OF THE ERROR WITH RESPECT TO EACH COEFFICIENT ARE
FORMED AND SET EQUAL TO ZERO, A SYSTEM OF LINEAR EQUATIONS IS
FOUND, WHICH MAY THEN BE SOLVED TO YIELD OPTIMUM VALUES FOR THE
PARAMETERS.

COMMON/AL,AL1,AL2,AL3,AL4,AL5
COMMON/B,K,PD,Z,W,KY,DEPTH
COMMON/B/START,YSIN(50,200),KS,(100),QPROD(100)
COMMON/C/R(50),CAVG(50),CSURF(100),CS(100),TIM(100)
DIMENSION R(50,50),C(50),CDIF(50)
DIMENSION UL(50,50),GX(50)
CHARACTER*10 AL1,AL2,AL3,AL4,AL5

K5=0

CALL CALCULATE LINEAR EQUATIONS

M1=1
DO 10 K=1,M1
10 R(I,K)=0.0
DO 11 J=1,M1
11 R(I,J)=R(I,K)*YSIN(K-1,J)/((K-1)*W)
DO 12 K=2,M1
12 R(I,J)=R(I,J)/2.0
DO 13 J=1,M1
13 R(I,J)=R(I,J)*YSIN(K-1,J)/((K-1)*W)
DO 14 K=2,M1
14 R(I,J)=R(I,J)/2.0
DO 15 J=1,M1
15 R(I,J)=R(I,J)*YSIN(K-1,J)/((K-1)*W)
DO 16 K=2,M1
16 R(I,J)=R(I,J)/2.0
DO 17 J=1,M1
17 R(I,J)=R(I,J)*YSIN(K-1,J)/((K-1)*W)
DO 18 K=2,M1
18 R(I,J)=R(I,J)/2.0
DO 19 J=1,M1
19 R(I,J)=R(I,J)*YSIN(K-1,J)/((K-1)*W)

CALL SOLVE

CALL DECOMP(KP,P,UL,KS)
IF(KP,GT,0) STOP
CALL SOLVE(KP,UL,GO)

STORE OPTIMUM VALUES FOR THE PARAMETERS IN B.

DO 40 J=1,KP
40 B(J)=BO(J)/2.0
RETURN

END
SUBROUTINE COMPAR

SUBROUTINE COMPAR CALCULATES PREDICTED CONCENTRATIONS USING THE EQUATION FOR DOWNSTREAM CONCENTRATION. ERROR IN CALCULATION IS EXPRESSED AS THE SUM OF SQUARED ERRORS BETWEEN OBSERVED AND CALCULATED DOWNSTREAM CONCENTRATIONS.

COMMON/AL/AL1,AL2,AL3,AL4,AL5
COMMON/AW,EK,KD,Z,W,KT,DEPTH
COMMON/B/START,YSIN(50,100),U(100),OPRD(100)
COMMON/C/G(50),CVD(100),CSURF(100),CS(100),TIM(100)
DIMENSION O(50),SUM(50),CPRED(100)
CHARACTER*10 AL1,AL2,AL3,AL4,AL5

DO 9 J=1,10

CALCULATE AND STORE PARTS OF THE EQUATION

DO 10 J=1,10

SUM(J)=0.0
DO 10 J=1,10

10 SUM(J)=SUM(J)+(G(M)/(M-1)*W)*YSIN((M-1)/J)

CPRED(J)=CAVG(J)+U(J)*(R(J)+TIM(J)+G1*SUM(J)

PRINT TIME AND CALCULATED AND OBSERVED VALUES

11 PRINT 1070,TIME(J),CPRED(J),CAVG(J)
1070 FORMAT(1X,F6,2,F3X,E14,7,F3X,E14,7)

CALCULATE AND PRINT SUM OF SQUARED ERRORS

Z=0.0
DO 15 J=1,10

15 Z=Z+(CPRED(J)-CAVG(J)**2
PRINT 1080,1
1080 FORMAT(1X,22H(1)SUM OF SQUARED ERRORS,E14,7)

PRINT 1090
1090 FORMAT(1X,G,0.4,TIME,5X,H3P=-R)
DO 110 J=1,10

T=J*(TJ+1.0)*DT
Y(J)

CALCULATE AND PRINT GROSS PRODUCTION

DO 115 IS=1,10

115 G(1)=1

100 Y(1)=G(1)*COS(35*WT)
TIME(*)=START
108 IF(TIME,GT,24.0) GO TO 109
PRINT 1100,TIME,Y
1100 FORMAT(1H,F6,2,F3X,E15,8)
GO TO 110
109 TIME=TIME-24.0
GO TO 108
CONTINUE
RETURN
END
SUBROUTINE INTERP(MATI(N),MATO(KT),TIM(N))

C THIS SUBROUTINE CALCULATES REGULARLY SPACED VALUES OF A
C QUANTITY FROM ERRATICALLY SPACED INPUT VALUES.

REAL MATI(N),MATO(KT),TIM(N)

DO 201 I=1,KT
  MATO(I)=0.0
  NIT=KT
  IT=0
  DO 1 J=1,KT
    TJ=(J-1)*DT
    IF(TJ.LE.TIM(1)) GO TO 2
    IF(TJ.GE.TIM(N)) GO TO 3
    GO TO 1
  2  MATO(J)=MAT(1)
    IT=IT+1
    GO TO 1
  3  MATO(J)=MAT(I)
    NIT=NIT-1
  1 CONTINUE
  NNI=1
  DO 9 IA=1,NN
    IA=(TIM(1)/DT)+1.0
    IF(IA.LT.1) IA=1
    IF(IA.GT.N) IA=N
    MATO(IA)=MAT(1)
    MATO(IA+1)=MATO(IA)
    INT=IA-1
    IF(INT.LE.0) GO TO 9
    DIFF=(MATO(IA)-MATO(IA))/INT
    IF(DIFF.NE.0.0) GO TO 12
    DO 12 IA=1,INT
      IA=IA+1
      MATO(IA)=MATO(IA-1)
      GO TO 9
  9  CONTINUE
  12  MATO(KT)=MATO(IA)
       GO TO 9
  13 TIM=INT-1
  14  DO 8 J=1,INT
       MATO(J)=MATO(J)+DIFF
       CONTINUE
  15  CONTINUE
  16  DO 200 I=1,KT
      DO 201 I=1,KT
  200  CONTINUE
  RETURN
END
SUBROUTINE OXYPLOT(XPT, X1, X2, XVAL, CVAL, YMIN, YMAX, X)

    THIS SUBROUTINE PLOTS OXYGEN CONCENTRATION AGAINST TIME

COMMON XAVAK,XT,KB,Z,N,W,KT,DEPTH
COMMON B/START,YSIN(50,100),UI(100),OPROD(100)

The remainder of this subroutine is identical with OXYPLOT
listed in Appendix A.

SUBROUTINE PLOT(XPT, VAL, IX, XVAL, CVAL)

    THIS SUBROUTINE PLOTS OXYGEN PRODUCTION AGAINST TIME.

COMMON XAVAK,KT,KB,Z,N,W,KT,DEPTH
COMMON B/START,YSIN(50,100),UI(100),OPROD(100)

The remainder of this subroutine is identical with PLOT
listed in Appendix A.
### Table A1

**Definition of FORTRAN Variables**

<table>
<thead>
<tr>
<th>FORTRAN Identifier</th>
<th>Definition</th>
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<tbody>
<tr>
<td>CAVG</td>
<td>Average oxygen concentration over depth</td>
</tr>
<tr>
<td>CSURF</td>
<td>Surface oxygen concentration</td>
</tr>
<tr>
<td>DEPTH</td>
<td>Depth</td>
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<tr>
<td>RAD</td>
<td>Radiation</td>
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<tr>
<td>SAL</td>
<td>Salinity</td>
</tr>
<tr>
<td>TEMP</td>
<td>Surface temperature</td>
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<tr>
<td>TIM</td>
<td>Time at which data are collected</td>
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### Table B2

**Cards for Input to Standing Water, Depth Average Program**

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<tr>
<th>Card Number</th>
<th>Variables</th>
<th>Format</th>
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<tbody>
<tr>
<td>1</td>
<td>NUMB</td>
<td>12</td>
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<tr>
<td>2</td>
<td>AL1,AL2,AL3,AL4,AL5</td>
<td>5A10</td>
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<tr>
<td>3</td>
<td>KRAD,THRS</td>
<td>12,F10</td>
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<tr>
<td>4</td>
<td>SAL,DT,PRES,N,KO</td>
<td>I6,2F10,2I5</td>
</tr>
<tr>
<td>5</td>
<td>AK,START</td>
<td>2F10</td>
</tr>
<tr>
<td>6</td>
<td>DEPTH</td>
<td>F10</td>
</tr>
<tr>
<td>7 through N+7</td>
<td>TIM(I),CAVG(I),CSURF(I),TEMP(I)</td>
<td>Free field</td>
</tr>
<tr>
<td>N+8</td>
<td>F1,F2</td>
<td>2F10</td>
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Figure B1. Example of line printer plots for standing water depth averaged program (sheet 1 of 3)
10 JUIN 1969 - LOCATION 1-1 SAMPL.

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<th>MET PRODUCIVITY: OXIDE CUBIC &amp; MET PER CURIE METER PER HOUR</th>
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Figure Bl. (sheet 2 of 3)
APPENDIX C: STANDING WATER, DEPTH DISTRIBUTION PROGRAM

Input

1. Definitions of FORTRAN which have not already been given in Tables A1 and B1 are listed in Table C1. The order in which the cards are read and the appropriate formats are given in Table C2. The first card (NUMB) is required only before the initial day of data and the last card (F1, F2) is required only if radiation is not available.

Listing

2. A listing of the computer program follows.

Output

3. The output from this program is similar to the output from the programs described in Appendix A and Appendix B except that output for each depth in the water body is produced. Example output is shown in Figure C1.

4. The subroutines DECOMP, SOLVE, SING, OXYPLOT, PLOT, and RADPLT, which are part of this program, are identical with the subroutines of the same name in the program for average productivity in standing water (Appendix B).
This program calculates rates of photosynthesis and respiration in a lake community using a method developed by George H. Hornberger and Mahlon G. Kelly of the Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia. The program was written by George Hornberger and Virginia Hendry of that department. The subroutines DECOMP, SOLVE, and SING were copied with slight modifications from computer solution of linear algebraic systems by George E. Forsythe and Cleve R. Moler (Prentice-Hall, 1967).

Method

Oxygen measurements are taken in a lake at points separated by a constant vertical distance. The rate of change of oxygen concentration at a depth \( t \) may be represented by the equation:

\[
\frac{dc(t)}{dt} = \frac{(dV(t+1/2)*C(1)+dV(t-1/2)*C(1))}{2} - \frac{(dV(t-1/2)*C(1-1/2))}{2} + (P-R)(t)
\]

where \( C(1) \) = concentration at depth \( t \)
\( dV(1) \) = dispersion coefficient at depth \( t \)
\( 2 \) = distance between depths
\( (P-R)(t) \) = net productivity at depth \( t \)

The equation for the surface layer may be written:

\[
\frac{dc(t)}{dt} = 2 \frac{dV(t+1/2)*c(1)}{Z*2} + \frac{2*K*dV(t+1/2)}{Z*(dV(t+1/2)*c(1))}
\]

\[
\frac{(dV(t+1/2)*c(1))}{(dV(t+1/2)*c(1))} + (P-R)(t)
\]

\( K \) = respiration coefficient
\( c(t) \) = saturation concentration

Net productivity at any depth may be represented by a Fourier series:

\[
P-R = \frac{A0}{2} + \sum_{n=1}^{kmax} \left( A_n \cos(n \pi t) \right)
\]

where \( A_n \) = coefficients
\( \pi \) = period of observation
\( t \) = time

These equations may be integrated exactly and solved using observed concentrations, for the Fourier coefficients so that a continuous function for net productivity may be calculated for each depth.

Since exchange with bottom sediments cannot be defined, no productivity estimates are made for the bottom layer.
READ IN NUMBER OF DAYS TO RUN

READ 19:NUMB
   19 FORMAT(12)
   NCMK*0

READ IN ALPHANUMERIC CHARACTERS FOR LOCATION AND DATE

READ 5000,AL1,AL2,AL3,AL4,AL5
   5000 FORMAT(5A10)

READ IN DATA MODE INFORMATION

KRAD=0   NO RADIATION DATA AVAILABLE
   *1 RADIATION MEASURED

THR$:THRESHOLD VALUE FOR RADIATION

READ 20:KRAD,THRS
   20 FORMAT(1,9.4)

READ IN Z#THICKNESS OF LAYERS
   DT=DATA INTERVAL

READ 5,Z,DT,PRES,N,KD,IX
   5 FORMAT(3F10.0,3I5)
   IX=IX

READ IN PK#EGERATION COEFFICIENT

READ 10:PK,START
   10 FORMAT(2F10.0)

INITIALIZE ARRAYS
IF -- ' .-.- ----

DO 220 J=1,N

DO 221 J=1,N

READ IN DISPERSION COEFFICIENT FOR EACH DEPTH (METERS SQUARED PER HOUR)

DO 600 I=1,N

READ 25, DV(I)

FORMAT(F10.0)

DV(I)=DV(I)

IX=LX-2

DO 601 I=1,N

DV(I)=DV(I)+DV(I+1)/2.0

READ IN TEMPERATURE (DEGREES CENTIGRADE)

IF RAD>EQ.0 READ 6100,CS(I)

IF RAD>GT.0 READ 6100,CS(I),RAD(I)

READ IN DISSOLVED CONCENTRATIONS (GRAMS PER CURRIC METER)

DO 620 J=1,N

READ 6100,DC(I,J),J*1.1XS

READ IN NUMBER OF DEPTHS TO BE PLOTTED

READ 638,MR

FORMAT(I3)

IF (MR.EQ.0) GO TO 18

READ IN DEPTHS TO BE PLOTTED

DO 631 I=1,MR

READ 630,N(I)

IF NO RADIATION DATA IS AVAILABLE, READ IN TIME OF SUNRISE AND SUNSET

4 IF (KRAD.LT.0) READ 4,F1,F2

1 FORMAT(2F10.0)

11=(F1-START)/DT+1.0

12=(F2-START)/DT+1.0

DAY=FLOAT(DAY)+T

DT=24HOURS/(2.0*DAY)
CONVERT TEMPERATURE TO SATURATION CONCENTRATION OF OXYGEN

SATURATION FOR ATMOSPHERIC PRESSURE

619 DO 70 I=1,N
CS(I)=AI-A2*CS(I)+A3*CS(I)**2+A4*CS(I)**3- A5*CS(I)**4+A6*CS(I)**5
70 CS(I)=CS(I)*CPRR

CALCULATE THE INTEGRAL OF RADIATION OVER THE INTERVAL FROM SUNRISE TO SUNSET, USING THE TRAPEZOIDAL RULE

PRINT 0,0
IF(KRAD.EQ.0, GO TO 750
IF(RAD(I).GT.TWRS) GO TO 750
I=10000
DO 740 I=1,N
IF(RAD(I).LE.THRS) GO TO 730
IF(I.IG.THRS) I=I-1
RINT=RINT+(RAD(I-1)+RAD(I))*DT
12=1+1
GO TO 740
730 IF(I.EQ.1) GO TO 740
IF(RAD(I-1).LE.THRS) GO TO 740
PRINT*(RAD(I-1)+RAD(I))*DT*RINT
740 CONTINUE
IF(I.EQ.0) I=I+1
RINT=60.0/2.0
IF(RAD.EQ.0) KRAD=0
750 CONTINUE
DO 555 I=1,1X

PRINT HEADINGS

PRINT 4000
6000 FORMAT(1H1,50H******************************************************************************)
PRINT 1640
1040 FORMAT(1H90,50H******************************************************************************)
PRINT 10200
1070 FORMAT(1H22HNET PRODUCTIVITY-DEPTH,13,/) PRINT 1040
PRINT 5001,AL1,AL2,AL3,AL4,AL5
5001 FORMAT(1H9,5A10)
PRINT 1040

AK=2.*DV(I)/Z**2
AK=AK*(1.-RK*7/DV)
IF(I.IG.T) AK=(DV(I)+DV(I-1))/Z**2
SEXP=-AK*DT

SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS (PARAMETERS)
CALL PARAM(JK)

PRINT VALUES OF PARAMETERS

PRINT 1020
1020 FORMAT(1H0,17PARAMETER VALUES=)
DO 210 I=1,JK
210 PRINT 1030,I,G(I)
1030 FORMAT(1H1,12,2X,E15.8)
PRINT 1040
PRINT 1050
1050 FORMAT(1H0,20OXYGEN CONCENTRATION)
PRINT 1060
1060 FORMAT(1H1,2X,4HTIME,4X,9HPREDICTED,11X,9HOBSERVED)
IF(I.EQ.1) PRINT 1061
1061 FORMAT(1H1,5X,9Hsaturation)

SUBROUTINE COMPAR CALCULATES DOWNSTREAM OXYGEN CONCENTRATIONS FROM
UPSTREAM DATA AND COMPARES CALCULATED AND OBSERVED VALUES

CALL COMPAR(JK)

INTEGRATE PRODUCTION OVER THE DARK INTERVALS AND DIVIDE BY THE
LENGTH OF THE INTERVALS TO CALCULATE MEAN RESPIRATION

RMEAN=0.0
IF(RADI GT THRS) GO TO 213
RMEAN=RMEAN*+PROD(I,11)
DO 212 I=1,JK
212 RMEAN=RMEAN-(PROD(I,11)*PROD(I,11)*PROD(I,11)*PROD(I,11))/2.0
RMEAN=DAY*RMEAN/OR

CALCULATE NET AND GROSS PRODUCTION OF OXYGEN

213 FNET=DAY*G(I)
FNET=FNET+RMEAN
IF(KRANGE LE 1) GO TO 9

PRINT PRODUCTION, RESPIRATION AND RADIATION DATA

PRINT 8,FNET,RMEAN,FGROS
8 FORMAT(1H0,15HNET PRODUCTION=F7.2,3X,12HRESPIRATION=F7.2,3X,17HG
ROSS PRODUCTION=F7.2,3X,27H2O RADIATION DATA AVAILABLE)
GO TO 214

9 PRINT 230,FNET,RMEAN,FGROS,PRINT
230 FORMAT(1H0,15HNET PRODUCTION=F7.2,3X,12HRESPIRATION=F7.2,3X,17HG
CALCULATE MAXIMUM AND MINIMUM VALUES FOR CONCENTRATION

DO 510 J=1,N
IF(DO(J*II),LT,VMIN) VMIN=DO(J*II)
510 IF(DO(J*II).GT.VMAX) VMAX=DO(J*II)

CALL SUBROUTINE TO PLOT OXYGEN CONCENTRATION

PRINT 6001,AL1,AL2,AL3,AL4,AL5,II
6001 FORMAT(H15,5A10,30H OXYGEN AND SATURATION AT DEPTH,13)
DO 591 K=1,N
591 DUMMY(K)=DO(K,JII)
CALL OXYPLOT(N,DUMMY,C5,0,DT,VMIN,VMAX,NK,JK)

CALL SUBROUTINE TO PLOT OXYGEN PRODUCTION

PRINT 6002,AL1,AL2,AL3,AL4,AL5,II
6002 FORMAT(H15,5A10,30H NET PRODUCTION AT DEPTH,13)
DO 591 K=1,N
591 DUMMY(K)=PROD(K,JII)
CALL PLOT(N,DUMMY,NK,3,0,DT)

CALL SUBROUTINE TO PLOT RADIATION AGAINST PRODUCTION

IF(KRAD.EQ.Q) CALL RADPLOT(N,DUMMY,RAD,START,DT)

PRINT A SUMMARY OF CALCULATIONS

RA05 NO 560 IE=1,2
RA066 FORMAT(161,12)****** SUMMARY ******,5X,5A10,///
PRINT RA067,II
RA067 FORMAT(161,12)DEPHT,13)
PRINT RA071,II
RA071 FORMAT(140,29X,14H NET PRODUCTION,3X,F7.2,3X,36HGRAMS OXYGEN PER CU METER PER DAY)
PRINT RA072,II
RA072 FORMAT(170,12)RESPIRATION=,5X,F7.2,3X,36HGRAMS OXYGEN PER CURT +C METER PER DAY)

C7
PRINT 8073,F900S
8073 FORMAT(1H ,25X,17HGROSS PRODUCTION-,F7,2,3X,36HGRAMS OXYGEN PER DU
+1IC METER PER DAY)
IF(KRAD.EQ.0) GO TO 560
PRINT 8074,INT
8074 FORMAT(1H ,25X,16HTOTAL RADIATION-,1X,F7,2,3X,36HLANDDEYS)
SLOPE=SQR(500.0) / RINT
PRINT 8075,SLOPE
8075 FORMAT(1H5,25X,6HSLOPE-,6X,F7,3,5X,36H(RATIO OF GROSS PROD. TO TOT
+AL RAD,1)
IF(INDEX.LT.1) GO TO 560
PRINT 8076,DUMMY(1)
8076 FORMAT(1H ,25X,37X,F7,3,5X,17H(FROM REGRESSION))
PRINT 8077,DUMMY(2)
8077 FORMAT(1H ,25X,10HINTERCEPT-,2X,F7,3)
PRINT 8078,DUMMY(3)
8078 FORMAT(1H ,25X,12HCORRELATION-,F7,3,\\)
560 CONTINUE
565 CONTINUE
NCOK=NCOK+1
IF(NCHK.GE.NUMB) STOP
GO TO 9000
END
FUNCTION CSI(I,J)

COMMON/START,DT
COMMON/CO,XO,1X,2,RK,1,S
COMMON/DV,DV1,DV(50)
COMMON/AV,C(100),G(20),N(100,50),PRON(100,90)
IF(1.EQ.1) GO TO 100

MIDDLE LAYERS
AK=(DV(I+1)+DV(I-1))/2*.2
AL=DV(I)/2*.2
AM=DV(I-1)/2*.2
AV=(DO(J*I+1)+DO(J*I))/2.0
AV=AV+AL
AVC=(DO(J-I-1)+DO(J-I))/2.0
AV=AV+AVC
CSS=(AV+AVC)/AK
CSI=CSS*(1.0-S)
RETURN

TOP LAYER
100 AKP=-DV(I)/2*.2
AK=AK-(2.*AV+AVC)/(DV1*7)
ALE=AV+DV(I)/2*.2
AME=AM+DV(I)/2*.2
AV=(DO(J*I+1)+DO(J*I))/2.0
AV=AV+AL
AVC=(AV+AVC+C(1))/2.0
AV=AV+AVC
CSS=(AV-AVC)/AK
CSI=CSS*(1.0-S)
RETURN
END
SUBROUTINE PARAN11

SIMULATE FLUX CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
(PARAMETERS). THE COEFFICIENTS MUST BE CHOSEN TO MINIMIZE THE
ACCUMULATIVE ERROR, EXPRESSED AS THE SUM OF SQUARES ERRORS BETWEEN
OBSERVED AND CALCULATED DOWNSTREAM CONCENTRATIONS. WHEN PARTIAL
DERIVATIVES OF THE ERROR WITH RESPECT TO EACH COEFFICIENT ARE
FORMED AND SET EQUAL TO ZERO, A SYSTEM OF LINEAR EQUATIONS IS
FOUND, WHICH MAY THEN BE SOLVED TO YIELD OPTIMUM VALUES FOR THE
PARAMETERS.

COMMON/V,START,DT
COMMON/AR(100),G(20),ZD(100,50),PROD(100,50)
COMMON/AL(AL),AI(AL),AI(AL),AI(AL,AL,AK)
CHARACTER*10 AL1,AL2,AL3,AL4,AL5

I=1:5
J=1:5
K=1:5
U(100,20),B(20,20),A(100),UL(20,20)

1000 40=0((i-1)*w+1(J-1)*DT)
1100 40=0((i-1)*w+1(J-1)*DT)
1200 40=0((i-1)*w+1(J-1)*DT)
1300 40=0((i-1)*w+1(J-1)*DT)

BREAK DOWN THE EQUATION FOR DOWNSTREAM CONCENTRATION INTO ITS
COMPONENT PARTS A, B1 AND GAM

DO 10 J=1,N
DO 20 I=1,N
20 I=1:N
GAM(L)+G0
DO 30 I=1,N
30 I=1:N

SET UP MATRICES B AND C TO CONTAIN THE LINEAR SYSTEM FOUND FROM
MINIMIZING THE ERROR, SUCH THAT B=A=C (WHERE MATRIX A CONTAINS
THE PARAMETERS)

DO 30 I=1,N
30 I=1:N
R(I,J)+0
R(I,J)+0
R(I,J)+0

SUMMARY

C10
DO 30 L=1,N

R(L,K)=R(L,K)+GAM(L,K)

35 C(K)=C(K)*GAM(L,K)*(B(L+1,I)-A(L))

40 R(K,1)=R(K,1)*P(1,K)

DO 30 L=1,N

C(L,I)=U(I,L)*B(L+1,I)-A(L)

CALL SUBROUTINES TO SOLVE THE SYSTEM OF LINEAR EQUATIONS BY GAUSSIAN ELIMINATION. IF A SINGULAR MATRIX IS FOUND, STOP EXECUTION.

81 CALL DECOMP(X,B,U,L,K,S)

IF(KS,LT,0) STOP

CALL SOLVE(KL,U,L,C,G)

G(I)=G(I)/P(I)

N=N+1

RETURN

END
PRINT 1090
1090 FORMAT(140,4+TIME,5X,3HP-R)
MM=MM+1
DO 110 J=1,NA
Y=H(I)
DO 100 IS=2,40
100 Y=H(IS)*\COST(IS,J)
PRM<(J,1)=Y
TIME=START-(J-1)*BT
PRINT 1100 TIME*Y
1100 FORMAT(1HT,6E,2,5X,E15.8)
110 CONTINUE
N=N+1
RETURN
END
### Table C1

**Definitions of FORTRAN Variables**

<table>
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<th>FORTRAN Identifier</th>
<th>Definition</th>
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<tbody>
<tr>
<td>DO(I,J)</td>
<td>Dissolved oxygen at time I and depth J</td>
</tr>
<tr>
<td>DV</td>
<td>Dispersion coefficient</td>
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<tr>
<td>IX</td>
<td>Number of depths at which data are collected</td>
</tr>
<tr>
<td>MR</td>
<td>Number of depths for which a line printer graph is desired</td>
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<tr>
<td>RK</td>
<td>Reaeration coefficient</td>
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<td>Z</td>
<td>Depth interval</td>
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### Table C2

**Cards for Input to Standing Water, Depth Distribution Program**

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<td>1</td>
<td>NUMB</td>
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<tr>
<td>2</td>
<td>AL1,AL2,AL3,AL4,AL5</td>
<td>5A10</td>
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<tr>
<td>3</td>
<td>KRAD,THRS</td>
<td>I2,F10</td>
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<tr>
<td>4</td>
<td>Z,DT,PRES,N,KO,IX</td>
<td>3F10,3F15</td>
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<tr>
<td>5</td>
<td>RK,START</td>
<td>2F10</td>
</tr>
<tr>
<td>6 through 1X+6</td>
<td>DV(I)</td>
<td>F10</td>
</tr>
<tr>
<td>IX+7 through</td>
<td></td>
<td>Free field</td>
</tr>
<tr>
<td>N+IX+7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N+IX+7 through</td>
<td>CS(I),RAD(I)</td>
<td></td>
</tr>
<tr>
<td>2N+IX+7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2N+IX+8</td>
<td>MR</td>
<td>I3</td>
</tr>
<tr>
<td>2N+IX+9</td>
<td>F1,F2</td>
<td>2F10</td>
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Figure Cl. Sample output, standing water depth distribution program (sheet 1 of 3)
Figure C1. (sheet 2 of 3)
### NET PRODUCTIVITY VERSUS RADIATION

**NET PRODUCTIVITY, GRAMS OXYGEN PER CUBIC METER PER HOUR**

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**Figure C1. (sheet 3 of 3)**
APPENDIX D: NOTATION

A  Area
A_n  Fourier coefficient
C  Dissolved oxygen concentration
c_s  Saturation concentration of dissolved oxygen
d  Total depth for standing water
D_v  Vertical dispersion coefficient
K  Reaeration coefficient
P  Gross productivity
Q  Vertical flow
R  Respiration
t  Time
V  Velocity
X  Horizontal distance
z  Vertical distance
δ  Residence time
κ  Gas exchange coefficient
ω  2π/48
In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Virginia. University.

Methods of dissolved oxygen budget analysis for assessing effects of dredged material disposal on biological community metabolism, by George M. Hornberger and Mahlon G. Kelly. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1975.

1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Contract report D-75-3)

Prepared for Environmental Effects Laboratory, U. S. Army Engineer Waterways Experiment Station, under Contract No. DAALW-74-C-0030, (DMRP Work Unit 1D04)

Includes bibliography.


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