DREDGED MATERIAL RESEARCH PROGRAM

CONTRACT REPORT D-75-3

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

by

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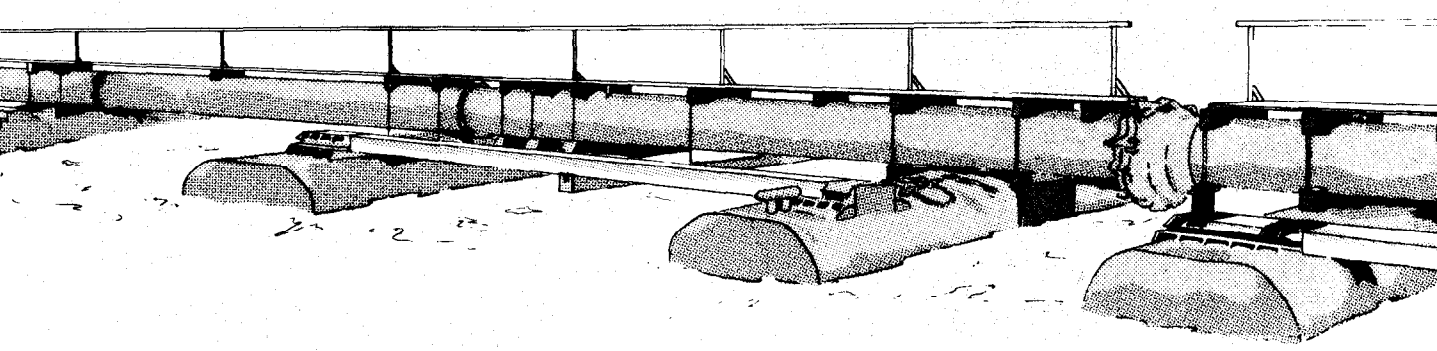

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U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

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SUBJECT: Transmittal of Contract Report D-75-3

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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
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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

(Continued)

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20. ABSTRACT.

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.

PREFACE

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 Virigina. 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 solutions found.[1] Open-water disposal occurs in a wide variety of environments 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 widespread applicability. Short-term effects resulting from changes in turbidity, 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 community 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 pollution 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 photosynthesis 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.[2] 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.[3,4] 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.[4,5] 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[6] 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.:[1] 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[3,7]

$$\frac{dx}{dt} = V \tag{1a}$$

$$\frac{dc}{dt} = K(c_s - c) + P - R \tag{1b}$$

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:[4]

$$P - R = \frac{A_0}{2} + \sum_{n=1}^{\infty} A_n \cos n\omega t \tag{2}$$

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:

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

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

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

Time t_{j+1} is the time at which water present at the upstream station at time t_j reaches the downstream station, δ 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

$$J = \sum_{j=1}^{M} \left[c_{j+1}^{(o)} - c_{j+1}^{(p)} \right]^2 \tag{3b}$$

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 $\left(c_{j+1}^{(p)} \right.$ is given by Equation 3a$\left.\right)$ 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.[9]

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[5,9,10]

$$\frac{\partial c}{\partial t} + \frac{Q}{A} \frac{\partial c}{\partial z} = \frac{1}{A} \frac{\partial}{\partial z} \left(D_v A \frac{\partial c}{\partial z} \right) + P-R \tag{4}$$

where

c = oxygen concentration (ML^{-3})

t = time (T)

Q = vertical flow (L^3T^{-1})

A = horizontal area (L^2)

z = vertical distance (L)

D_v = the vertical dispersion coefficient (L^2T^{-1})

P-R = net community productivity (MT^{-1})

A further simplification of Equation 4 is obtained if vertical advection is negligible[11] or considered to be accounted for by a dispersion term.[10] The mass-balance equation for oxygen then reduces to

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left(D_v \frac{\partial c}{\partial z}\right) + P\text{-}R \tag{5}$$

16. 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

$$\frac{\partial \bar{c}}{\partial t} = \frac{D_v}{d} \frac{\partial c}{\partial z}\bigg|_o^d + \overline{P\text{-}R} \tag{6}$$

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 κ 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

$$\frac{d\bar{c}}{dt} = \frac{K}{d}(c_s - c_1) + \overline{P\text{-}R} \tag{7}$$

17. $\overline{P\text{-}R}$ 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

$$\bar{c}_{j+1} = \bar{c}_j + \int_{t_j}^{t_{j+1}} K(c_s - c_1)\, dt + \frac{A_0 \delta}{2}$$

$$+ \sum_{n=1}^{N} \frac{A_n}{n\omega} (\sin n\omega t_{j+1} - \sin n\omega t_j) \tag{8}$$

In this case $\bar{c}_j$ and $\bar{c}_{j+1}$ 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

$$\sum_{j=1}^{M} \left[\bar{c}_{j+1}^{(o)} - \bar{c}_{j+1}^{(p)} \right]^2$$

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 Δz above and below with a solution to Equation 5.[5] Using the subscript i to denote depths at which measurements are taken, the dispersion term of Equation 5 can be approximated

$$\frac{\delta}{\delta z}\left(D_v \frac{\delta c}{\delta z}\right) \approx \frac{1}{(\Delta z)^2} \left[D_{v_{i+1/2}} c_{i+1} - \left(D_{v_{i+1/2}} + D_{v_{i-1/2}} \right) c_i + D_{v_{i-1/2}} c_{i-1} \right] \tag{9}$$

where

$D_{v_{i+1/2}}$ = the dispersion coefficient between depth i and depth $i+1$; $D_{v_{i-1/2}}$ is similarly defined.

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

$$(P-R)_i = \frac{A_0^i}{2} \sum_{n=1}^{\infty} A_n^i \cos n\omega t \tag{10}$$

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 :

$$\frac{dc_i}{dt} = \frac{1}{(\Delta z)^2} \left[D_{v_{i+1/2}} c_{i+1} + \left(D_{v_{i+1/2}} + D_{v_{i-1/2}} \right) c_i + D_{v_{i-1/2}} c_{i-1} \right] + \frac{A_0^i}{2} + \sum A_n^i \cos n\omega t \tag{11}$$

Equation 11 can be treated as an initial value problem in c_i and solved to give:

$$c_i^{j+1} = e^{-U\delta} c_i^j + \frac{1}{e^{Ut_{j+1}}} \int_{t_j}^{t_{j+1}} (Vc_{i+1} + Wc_{i-1})\, e^{Ut}\, dt + \frac{A_0^i}{2U} \left(1 - e^{-U\delta}\right) + \sum_{n=1}^{N} \frac{A_n^i}{U^2 + (n\omega)^2} \Big[U \cos n\omega t_{j+1} + n\omega \sin n\omega t_{j+1} - e^{-U\delta} (U \cos n\omega t_j + n\omega \sin n\omega t_j) \Big] \tag{12}$$

where

$$U = \left(D_{v_{i+1/2}} + D_{v_{i-1/2}}\right)/(\Delta z)^2$$

$$V = D_{v_{i+1/2}}/(\Delta z)^2$$

$$W = D_{v_{i-1/2}}/(\Delta z)^2$$

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, of 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 reaeration 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.[4] 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, Welch[12] collected data at 0.25-m increments in Lago pond and Eley[13] and Wright[14] 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]

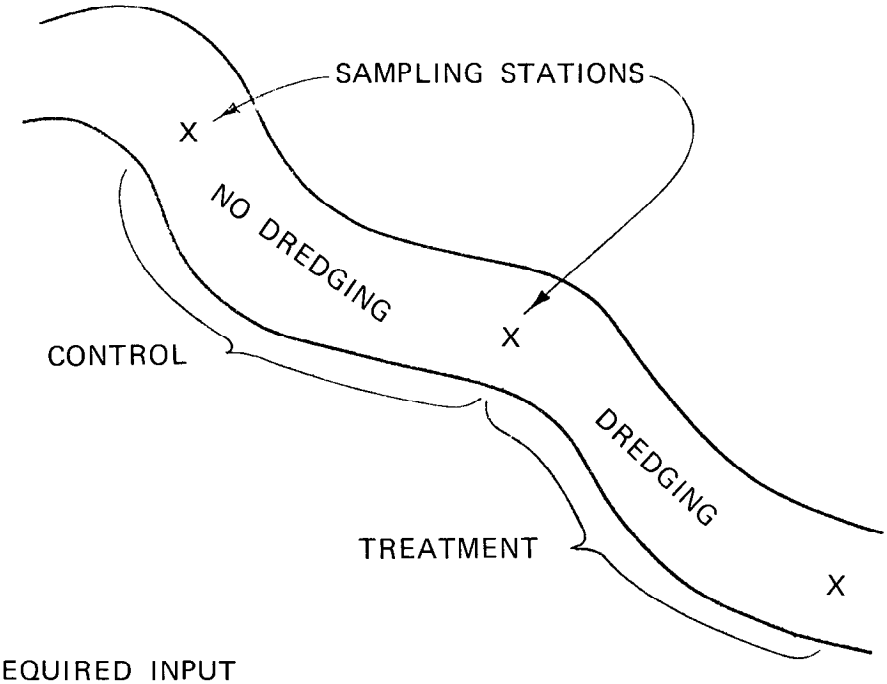
25. Provision of oxygen concentrations, temperature, salinity, reaeration coefficient, and dispersion coefficients as appropriate in the computer programs described in the appendices allows calculation of a time-continuous function describing net productivity. Saturation concentrations are calculated internally in the programs using a polynomial

fit to the data of Truesdale et al.[15] 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 than 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,[17-19] and the communities thus depend on allochthanous energy input. Nutrient enrichment modifies this such that P:R is greater than one and organic material may be exported downstream.[18] 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.[4] 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.



REQUIRED INPUT

REAERATION COEFFICIENT OR $\bar{x}$ DEPTH AND VELOCITY
RESIDENCE TIME
UPSTREAM DO, WATER TEMP, AND TIME OF MEASUREMENTS
DOWNSTREAM DO, WATER TEMP, AND TIME OF MEASUREMENTS

Figure 1. Application to a river segment

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.

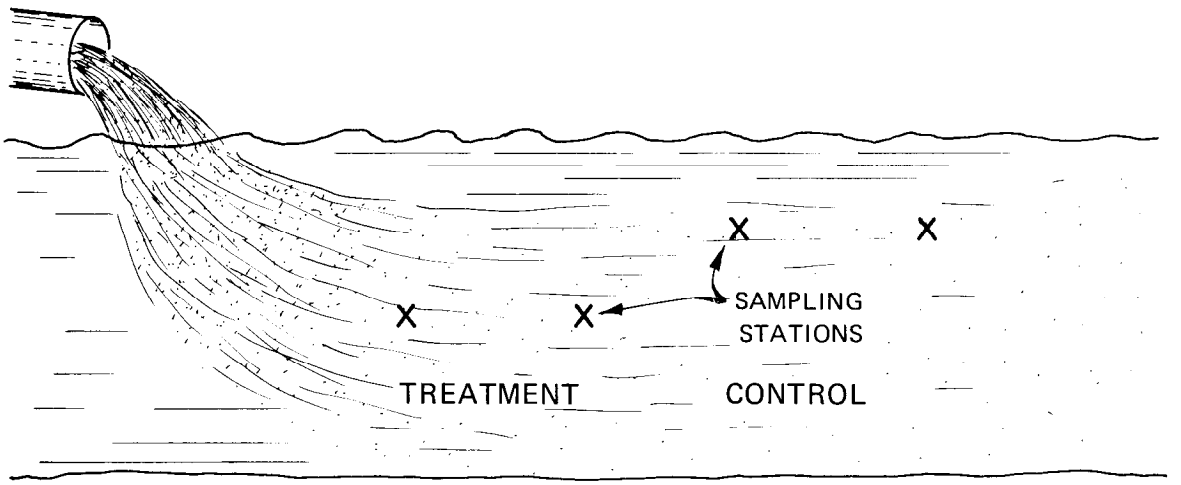


Figure 2. Application to standing water

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.

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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.

THIS PROGRAM CALCULATES RATES OF PHOTOSYNTHESIS AND RESPIRATION IN A RIVER COMMUNITY USING A METHOD DEVELOPED BY MAHLON G. KELLY, GEORGE M. HORNBERGER, AND B. J. COSBY AT THE DEPARTMENT OF ENVIRONMENTAL SCIENCES, UNIVERSITY OF VIRGINIA, CHARLOTTESVILLE, VIRGINIA. THE PROGRAM WAS WRITTEN BY GEORGE M. 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 B. MOLER (PRENTICE-HALL, 1967).

METHOD

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

```
DC/DT = K*(CS-C) + (P-R)
```

```
WHERE C  = CONCENTRATION
      CS = SATURATION CONCENTRATION
       K = REAERATION COEFFICIENT
     P-R = GROSS PRODUCTION
```

GROSS PRODUCTION MAY BE REPRESENTED BY A FOURIER SERIES

```
P-R = A0/2 + SUM FROM N=1 TO K0 OF (AN*COS(N*W*T))
```

```
WHERE AN = COEFFICIENTS
       W = PI/PERIOD OF OBSERVATION
       T = TIME
```

THE DIFFERENTIAL EQUATION MAY BE SOLVED FOR DOWNSTREAM CONCENTRATION

```
D(J+1) = EXP(-K*DELTA)*U(J)
         +(1/EXP(K*T(J+1))*INTEGRAL FROM T(J) TO T(J+1) OF
          (K*CS(T)*EXP(K*T)*DT)
         +(A0/2*K)*(1-EXP(-K*DELTA))
         +SUM FROM N=1 TO K0 OF (AN/(K**2+(N*W)**2))*
          (K*COS(N*W*T(J+1)) + N*W*SIN(N*W*T(J+1))
          -(EXP(K*DELTA))*(K*COS(N*W*T(J))+
          N*W*SIN(N*W*T(J))))
```

```
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.

```
C
      CHARACTER*10 AL1,AL2,AL3,AL4,AL5
      COMMON AK
      COMMON M,DT
      COMMON START,ZCOS(50,100),ZSIN(50,100),CSI(100)
      COMMON K0,Z
      COMMON DO(100),U(100),G(50)
      COMMON D,N,W,D1,S,K
      COMMON/AL/AL1,AL2,AL3,AL4,AL5,KODE
      COMMON/PR/PROD(100),UPROD(100),DPROD(100),QPROD(100)
      COMMON/T/THRS
      DIMENSION RM(5),PN(5),PG(5)
      DIMENSION USAV(100),USS(100),DS(100),US(100),SAV(100),SS(100)
      DIMENSION RAD(100)
      DIMENSION IFOR(3)
      DATA A1,A2,A3,A4,A5,A6/14.589,0.392503,6.34716E-03,1.42111E-04,
     +1.07386E-05,1.65321E-07/
C
C        READ IN NUMBER OF DAYS TO RUN
C
      READ 19,NUMB
   19 FORMAT(I2)
C
C        READ IN ALPHANUMERIC CHARACTERS FOR LOCATION AND DATE
C
      NCHK=0
 9000 IPRIN=0
      READ 5000,AL1,AL2,AL3,AL4,AL5
 5000 FORMAT(5A10)
C
C        READ IN DATA MODE INFORMATION
C
C              KODE=1  ALL METHODS
C                   =2  TWO STATION METHOD
C                   =3  SINGLE STATION (UPSTREAM)
C                   =4  SINGLE STATION (DOWNSTREAM)
C
C              KRAD=0  NO RADIATION DATA AVAILABLE
C                   =1  RADIATION MEASURED AT UPSTREAM STATION
C                   =2  RADIATION MEASURED AT DOWNSTREAM STATION
C
C
C              THRS=THRESHOLD VALUE OF RADIATION
C
      READ 20,KODE,KRAD,THRS
   20 FORMAT(2I2,F10.0)
C
C        READ IN  D=RESIDENCE TIME (HOURS)
C                DT=DATA INTERVAL (HOURS)
C              PRES=ATMOSPHERIC PRESSURE (MILLIBARS, CORRECTED TO SEA LEVEL)
C                 N=NUMBER OF DATA POINTS
C                K0=NUMBER OF PARAMETERS
```

```
C
      READ 5,D,DT,PRES,N,KO
    5 FORMAT(3F10.0,2I5)
C
C         READ IN     AK=REAERATION COEFFICIENT (METERS/HOUR)
C                   START=STARTING TIME (HOURS)
C
      READ 10,AK,START
   10 FORMAT(2F10.0)
C
C
C         INITIALIZE ARRAYS
C
      DO 600 I=1,N
      U(I)=0.0
      US(I)=0.0
      DO(I)=0.0
  600 DS(I)=0.0
C
C         READ IN OXYGEN DATA
C                U=UPSTREAM CONCENTRATION (GRAMS/CUBIC METER)
C              DO=DOWNSTREAM CONCENTRATION (GRAMS/CUBIC METER)
C              US=UPSTREAM TEMPERATURE (DEGREES CENTIGRADE)
C              DS=DOWNSTREAM TEMPERATURE (DEGREES CENTIGRADE)
C
  605 IF(KODE.EQ.4)   GO TO 609
  606 DO 607 I=1,N
C
C         READ IN UPSTREAM OXYGEN CONCENTRATION, TEMPERATURE, AND RADIATION
C
 6100 FORMAT(V)
      READ 6100,US(I),U(I),URAD
  607 IF(KRAD.EQ.1) RAD(I)=URAD
      IF(KODE.EQ.3.AND.KRAD.EQ.2) GO TO 6090
      IF(KODE.EQ.4) GO TO 6090
  608 IF(KODE.GE.3)  GO TO 3
  609 IF(KRAD.EQ.1.AND.KODE.EQ.4) GO TO 606
 6090 DO 610 I=1,N
C
C         READ IN DOWNSTREAM OXYGEN CONCENTRATION, TEMPERATURE, AND RADIATION
C
      READ 6100,DS(I),DO(I),DRAD
  610 IF(KRAD.EQ.2) RAD(I)=DRAD
    3 IF(KRAD.NE.0) GO TO 2
C
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)
      I1=F1/DT+1.0
      I2=F2/DT+1.0
```

```
    2 IF(NUMB.EQ.0) NUMB=1
      VMIN=1000.
      VMAX=0.
      K1=1
      KODE1=1
      KSAV=KODE
      DAT=D
      DAY=FLOAT(N-1)*DT
      W=6.28318/(2.0*DAY)
      M=D/DT+1.001
      PRINT 6000
 6000 FORMAT(1H1,50H**************************************************)
      CORR=(PRES+0.19)/29.92
      IF(PRES.GT.50.0) CORR=(PRES-17.0)/1013.25
  619 DO 70 I=1,N
C
C         CONVERT TEMPERATURE TO SATURATION CONCENTRATION OF OXYGEN
C
      US(I)=A1-A2*US(I)+A3*US(I)**2+A4*US(I)**3- A5*US(I)**4+A6*US(I)**5
      DS(I)=A1-A2*DS(I)+A3*DS(I)**2+A4*DS(I)**3- A5*DS(I)**4+A6*DS(I)**5
C
C         CORRECT SATURATION FOR ATMOSPHERIC PRESSURE
C
      US(I)=US(I)*CORR
      DS(I)=DS(I)*CORR
      SAV(I)=DO(I)
      SS(I)=DS(I)
      USAV(I)=U(I)
      USS(I)=US(I)
      IF(KODE.EQ.4)    GO TO 61
C
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).GT.VMAX) VMAX=US(I)
      IF(KODE.GE.3) GO TO 70
   61 CONTINUE
      IF(DO(I).LT.VMIN) VMIN=DO(I)
      IF(DO(I).GT.VMAX) VMAX=DO(I)
      IF(DS(I).GT.VMAX) VMAX=DS(I)
   70 CONTINUE
C
C         CALCULATE THE INTEGRAL OF RADIATION OVER THE INTERVAL FROM SUNRISE
C           TO SUNSET, USING THE TRAPEZOIDAL RULE
C
      RINT=0.0
      IF(KRAD.EQ.0) GO TO 750
      IF(RAD(1).GT.THRS)    GO TO 750
      I1=10000
      DO 740 I=1,N
      IF(RAD(I).LE.THRS)    GO TO 730
```

```
      IF(I1.GT.I) I1=I-1
      RINT=(RAD(I-1)+RAD(I))*DT+RINT
      I2=I+1
      GO TO 740
  730 IF(I.EQ.1) GO TO 740
      IF(RAD(I-1).LE.THRS)   GO TO 740
      RINT=RINT+(RAD(I-1)+RAD(I))*DT
  740 CONTINUE
      IF(I1.EQ.0) I1=1
      RINT=RINT*60.0/2.0
      IF(RINT.EQ.0) KRAD=0
  750 CONTINUE
C
C        PRINT HEADINGS
C
      PRINT 1041,AK,K0,D
 1041 FORMAT(1H ,50X,13HREAER. COEF.-,F6.3,5X,11HPARAMETERS-,I2,5X,
     +10HRES. TIME-,F5.2)
      PRINT 5001,AL1,AL2,AL3,AL4,AL5
 5001 FORMAT(1H ,5A10)
      PRINT 1040
 1040 FORMAT(1H0,50H**************************************************)
      PRINT 975
  975 FORMAT(1H0,2X,34HUPSTREAM  DOWNSTR UPSTREAM DOWNSTR)
      IF(KRAD.NE.0) GO TO 948
      PRINT 980
  980 FORMAT(1H ,3X,40HOXYGEN   OXYGEN  SATURAT  SATURAT   TIME)
      GO TO 949
  948 PRINT 985
  985 FORMAT(1H ,3X,50HOXYGEN   OXYGEN  SATURAT  SATURAT RADIATION   TIM
     +E)
C
C        PRINT CONCENTRATION DATA AND TIME
C
  949 DO 950 I=1,N
      TIME=(I-1)*DT+START
      IF(KODE.EQ.3)   DS(I)=0.0
      IF(KODE.EQ.4)   US(I)=0.0
      IF(KRAD.NE.0) GO TO 9500
      PRINT 1005,U(I),DO(I),US(I),DS(I),TIME
 1005 FORMAT(1H ,6F9.4)
      GO TO 950
 9500 PRINT 1005,U(I),DO(I),US(I),DS(I),RAD(I),TIME
  950 CONTINUE
      N=N-M+1
C
C        PRINT HEADINGS
C
  295 IF(KODE.LT.3) PRINT 1070
 1070 FORMAT(1H1,35HNET PRODUCTIVITY-TWO STATION METHOD)
      IF(KODE.EQ.3) PRINT 1080
 1080 FORMAT(1H1,41HNET PRODUCTIVITY-SINGLE STATION(UPSTREAM))
```

```
      IF(KODE.EQ.4) PRINT 1090
 1090 FORMAT(1H1,43HNET PRODUCTIVITY-SINGLE STATION(DOWNSTREAM))
      PRINT 1040
      PRINT 5001,AL1,AL2,AL3,AL4,AL5
      PRINT 1040
      PRINT 1100
 1100 FORMAT(1H0,2X,38HDELTA NO. VALS. DAT/DELTA REAER  PRES.)
      NN=N+M-1
      PRINT 1110,D,NN,M,AK,PRES
 1110 FORMAT(1H ,F5.1,5X,I2,7X,I2,5X,F5.2,2X,F8.2)
  300 IF(KODE.EQ.3)   GO TO 310
      IF(KODE.EQ.4)   GO TO 320
      DO 71 I=1,N
      DO(I)=DO(I+M-1)
   71 DS(I)=DS(I+M-1)
      GO TO 350
  310 DO 315 I=1,N
      DO(I)=U(I+M-1)
  315 DS(I)=US(I+M-1)
      GO TO 350
  320 DO 325 I=1,N
      U(I)=SAV(I)
      US(I)=SS(I)
      DO(I)=SAV(I+M-1)
  325 DS(I)=SS(I+M-1)
C
C         CALCULATE PARTS OF THE EQUATION FOR DOWNSTREAM CONCENTRATIONS
C         AND STORE FOR CONVENIENCE.
C
  350 Z=M-1
      D1=D/Z
      LL=KO-1
      DO 700 L=1,NN
      AL=L
      T=D1*(AL-1.0)*W
      DO 700 IQ=1,LL
      V=IQ
      ZCOS(IQ,L)=COS(V*T)
  700 ZSIN(IQ,L)=SIN(V*T)
      IF(KODE.GT.4) GO TO 2001
      S=EXP(-AK*D)
      DO 2000 I=1,N
      AI=I
      A=(DS(I)-US(I))/D
 2000 CSI(I)=(US(I)-A/AK)*(1.0-S)+A*D
 2001 CONTINUE
C
C         SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
C            (PARAMETERS)
C
      CALL PARAM
C
```

```
C         PRINT VALUES OF PARAMETERS
C
      PRINT 1020
 1020 FORMAT(1H0,17HPARAMETER VALUES-)
      DO 210 I=1,K0
  210 PRINT 1030,I,G(I)
 1030 FORMAT(1H ,I2,2X,E15.8)
      PRINT 1040
      PRINT 1050
 1050 FORMAT(1H0,17HDOWNSTREAM OXYGEN)
      PRINT 1060
 1060 FORMAT(1H ,2X,4HTIME,4X,9HPREDICTED,11X,8HOBSERVED)
C
C         SUBROUTINE COMPAR CALCULATES DOWNSTREAM OXYGEN CONCENTRATIONS FROM
C         UPSTREAM DATA AND COMPARES CALCULATED AND OBSERVED VALUES
C
      CALL COMPAR
C
C         INTEGRATE PRODUCTION OVER THE DARK INTERVALS AND DIVIDE BY THE
C         LENGTH OF THE INTERVALS TO CALCULATE MEAN RESPIRATION
C
      RMEAN=0.0
      IF(RAD(1).GT.THRS)   GO TO 215
      QR=I1+N+M-1-I2
      IF(QR.EQ.0) QR=1
      DO 211 I=1,I1
  211 RMEAN=RMEAN+QPROD(I)
      IU=N+M-1
      DO 212 I=I2,IU
  212 RMEAN=RMEAN+QPROD(I)
      RMEAN=RMEAN-(QPROD(1)+QPROD(I1)+QPROD(I2)+QPROD(IU))/2.0
      RMEAN=DAY*RMEAN/QR
C
C         CALCULATE NET AND GROSS PRODUCTION OF OXYGEN
C
  215 PNET=DAY*G(1)
      PGROS=PNET-RMEAN
      IPRIN=IPRIN+1
      PN(IPRIN)=PNET
      RM(IPRIN)=RMEAN
      PG(IPRIN)=PGROS
      IF(KRAD.GE.1) GO TO 9
C
C         PRINT PRODUCTION, RESPIRATION AND RADIATION DATA
C
      PRINT 8,PNET,RMEAN,PGROS
    8 FORMAT(1H0,15HNET PRODUCTION=,F7.2,3X,12HRESPIRATION=,F7.2,3X,17HG
     +ROSS PRODUCTION=,F7.2,3X,27HNO RADIATION DATA AVAILABLE)
      GO TO 214
    9 PRINT 213,PNET,RMEAN,PGROS,RINT
  213 FORMAT(1H0,15HNET PRODUCTION=,F7.2,3X,12HRESPIRATION=,F7.2,3X,17HG
     +ROSS PRODUCTION=,F7.2,3X,16HTOTAL RADIATION=,F7.2)
```

```
  214 IF(KODE.NE.1) GO TO 400
      KODE=2
      KODE1=-1
  400 IF(KODE1.GE.0) GO TO 6030
      KODE=KODE+1
      IF(KODE.GT.4) GO TO 6030
      D=DT
      N=N+M-1
      M=2
      N=N-M+1
      GO TO 295
 6030 KODE=KSAV
      N=N+M-1
      NIX=N
      IX=0
 6031 IX=IX+1
      NIX=NIX-50
      IF(NIX.GT.0) GO TO 6031
      XV=3.0
C
C        CALL SUBROUTINES TO PLOT OXYGEN CONCENTRATION AND PRODUCTION
C        DATA OVER TIME AND PRODUCTION AGAINST RADIATION
C
      IF(KODE.EQ.4)   GO TO 6010
      PRINT 6001,AL1,AL2,AL3,AL4,AL5
 6001 FORMAT(1H1,5A10,30HUPSTREAM OXYGEN AND SATURATION)
      CALL OXYPLOT(N,USAV,USS,XV,DT,VMIN,VMAX,IX)
 6010 IF(KODE.EQ.3)   GO TO 6020
      PRINT 6002,AL1,AL2,AL3,AL4,AL5
 6002 FORMAT(1H1,5A10,32HDOWNSTREAM OXYGEN AND SATURATION)
      CALL OXYPLOT(N,SAV,SS,XV,DT,VMIN,VMAX,IX)
 6020 CONTINUE
      IF(KODE.GE.3) GO TO 6021
      PRINT 5002,AL1,AL2,AL3,AL4,AL5
 5002 FORMAT(1H1,5A10,18HTWO STATION METHOD)
      CALL PLOT(N,PROD,IX,XV,DT)
      IF(KRAD.NE.0) CALL RADPLT(N,PROD,RAD,START,DT)
      IF(KODE.EQ.2) GO TO 8000
      KODE=3
      KSAV=-1
 6021 IF(KODE.NE.3) GO TO 6022
      PRINT 5003,AL1,AL2,AL3,AL4,AL5
 5003 FORMAT(1H1,5A10,23HSINGLE STATION UPSTREAM)
 7001 CALL PLOT(N,UPROD,IX,XV,DT)
      IF(KRAD.NE.0) CALL RADPLT(N,UPROD,RAD,START,DT)
      IF(KSAV.GE.0) GO TO 8000
      KODE=KODE+1
 6022 IF(KODE.NE.4) GO TO 6023
      PRINT 5004,AL1,AL2,AL3,AL4,AL5
 5004 FORMAT(1H1,5A10,25HSINGLE STATION DOWNSTREAM)
 7002 CALL PLOT(N,DPROD,IX,XV,DT)
      IF(KRAD.NE.0) CALL RADPLT(N,DPROD,RAD,START,DT)
```

```
      GO TO 8000
 6023 IF(KODE.NE.5)GO TO 6024
      PRINT 5005,AL1,AL2,AL3,AL4,AL5
 5005 FORMAT(1H1,5A10)
      GO TO 7001
 6024 PRINT 5005,AL1,AL2,AL3,AL4,AL5
      GO TO 7002
 8000 NCHK=NCHK+1
      IF(IPRIN.EQ.3)  GO TO 7090
      IUP=1
      IDN=1
      GO TO 7095
 7090 KODE=1
      IUP=2
      IDN=3
 7095 KSUM=0
 8099 KSUM=KSUM+1
      IF(KSUM.LE.2)  GO TO 8005
      IF(NCHK.GE.NUMB) STOP
      GO TO 9000
C
C        PRINT A SUMMARY OF CALCULATIONS
C
 8005 PRINT 8066,AL1,AL2,AL3,AL4,AL5
 8066 FORMAT(1H1,27H*****      SUMMARY      *****,5X,5A10,///)
      IF(KODE.GT.2)   GO TO 8019
      PRINT 8067
 8067 FORMAT(1H0,18HTWO STATION METHOD)
      PRINT 8070,AK,KO,DAT
 8070 FORMAT(1H0,10X,11HREAERATION-,F5.2,5X,11HPARAMETERS-,I2,5X,15HRESI
     *DENCE TIME-,F5.2)
      PRINT 8071,PN(1)
 8071 FORMAT(1H0,25X,14HNET PRODUCTION,3X,F7.2,3X,36HGRAMS OXYGEN PER CU
     +BIC METER PER DAY)
      PRINT 8072,RM(1)
 8072 FORMAT(1H ,25X,12HRESPIRATION-,5X,F7.2,3X,36HGRAMS OXYGEN PER CUBI
     +C METER PER DAY)
      PRINT 8073,PG(1)
 8073 FORMAT(1H ,25X,17HGROSS PRODUCTION-,F7.2,3X,36HGRAMS OXYGEN PER CU
     +BIC METER PER DAY)
      IF(KRAD.EQ.0) GO TO 8009
      PRINT 8074,RINT
 8074 FORMAT(1H ,25X,16HTOTAL RADIATION-,1X,F7.2,3X,8HLANGLEYS)
      SLOPE=PG(1)*60.0/RINT
      PRINT 8075,SLOPE
 8075 FORMAT(1H0,25X,6HSLOPE-,6X,F7.3,5X,36H(RATIO OF GROSS PROD. TO TOT
     +AL RAD.))
      PRINT 8076,PROD(1)
 8076 FORMAT(1H ,37X,F7.3,5X,17H(FROM REGRESSION))
      PRINT 8077,PROD(2)
 8077 FORMAT(1H ,25X,10HINTERCEPT-,2X,F7.3)
      PRINT 8078,PROD(3)
```

```
8078 FORMAT(1H ,25X,12HCORRELATION-,F7.3,/////)
8009 IF(KODE.EQ.2) GO TO 8099
8019 IF(KODE.EQ.4)   GO TO 8012
8011 PRINT 8068
8068 FORMAT(1H0,23HSINGLE STATION,UPSTREAM)
     PRINT 8070,AK,K0,D
     PRINT 8071,RN(IUP)
     PRINT 8072,RM(IUP)
     PRINT 8073,PG(IUP)
     IF(KRAD.EQ.0) GO TO 8012
     PRINT 8074,RINT
     SLOPE=PG(IUP)*60.0/RINT
     PRINT 8075,SLOPE
     PRINT 8076,UPROD(1)
     PRINT 8077,UPROD(2)
     PRINT 8078,UPROD(3)
8012 IF(KODE.EQ.3)   GO TO 8099
     PRINT 8069
8069 FORMAT(1H0,25HSINGLE STATION,DOWNSTREAM)
     PRINT 8070,AK,K0,D
     PRINT 8071,RN(IDN)
     PRINT 8072,RM(IDN)
     PRINT 8073,PG(IDN)
     IF(KRAD.EQ.0) GO TO 8099
     PRINT 8074,RINT
     SLOPE=PG(IDN)*60.0/RINT
     PRINT 8075,SLOPE
     PRINT 8076,DPROD(1)
     PRINT 8077,DPROD(2)
     PRINT 8078,DPROD(3)
     GO TO 8099
     END
```

```
      SUBROUTINE PARAM
C
C         SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
C         (PARAMETERS).  THE COEFFICIENTS MUST BE CHOSEN TO MINIMIZE THE
C         CUMULATIVE ERROR, EXPRESSED AS THE SUM OF SQUARED ERRORS BETWEEN
C         OBSERVED AND CALCULATED DOWNSTREAM CONCENTRATIONS.  WHEN PARTIAL
C         DERIVATIVES OF THE ERROR WITH RESPECT TO EACH COEFFICIENT ARE
C         FORMED AND SET EQUAL TO ZERO, A SYSTEM OF LINEAR EQUATIONS IS
C         FOUND, WHICH MAY THEN BE SOLVED TO YIELD OPTIMUM VALUES FOR THE
C         PARAMETERS.
C
      COMMON AK
      COMMON M,DT
      COMMON START, ZCOS(50,100),ZSIN(50,100),CSI(100)
      COMMON K0,Z
      COMMON D0(100),U(100),G(50)
      COMMON D,N,W,D1,S,K
      COMMON/AL/AL1,AL2,AL3,AL4,AL5,KODE
      DIMENSION CON(100)
      DIMENSION B(50,50),GAM(100,50),A(100),C(50)
      DIMENSION UL(50,50),GX(50)
      CHARACTER*10 AL1,AL2,AL3,AL4,AL5
      KS=0
      Z=N
C
C         BREAK DOWN THE EQUATION FOR DOWNSTREAM CONCENTRATION INTO ITS
C         COMPONENT PARTS A, B1 AND GAM FOR CONVENIENCE.
C
      DO 10 I=1,N
   10 A(I)=CSI(I)+S*U(I)
      DO 20 L=1,N
      GAM(L,1)=0.0
      DO 20 IS=2,K0
      V=IS-1
      IV=IS-1
      LO=L+M-1
      W1=1.0/(AK**2+(V*W)**2)
      W2=AK*ZCOS(IV,LO)+V*W*ZSIN(IV,LO)-S*(AK*ZCOS(IV,L)+V*W*
     1ZSIN(IV,L))
   20 GAM(L,IS)=W1*W2
C
C         SET UP MATRICES B AND C TO CONTAIN THE LINEAR SYSTEM FOUND FROM
C         MINIMIZING THE ERROR, SUCH THAT B*A=C (WHERE MATRIX A CONTAINS
C         THE PARAMETERS).
C
      DO 30 I=2,K0
      DO 30 J=2,K0
      B(I,J)=0.
      DO 30 L=1,N
   30 B(I,J)=B(I,J)+GAM(L,J)*GAM(L,I)
      B1=(1.0-S)/(2.0*AK)
      B(1,1)=B1*Z
```

```
      DO 40 I=2,K0
      C(I)=0.
      B(1,I)=0.
      DO 35 L=1,N
      B(1,I)=B(1,I)+GAM(L,I)
   35 C(I)=C(I)+GAM(L,I)*(D0(L)-A(L))
   40 B(I,1)=B1*B(1,I)
      C(1)=0.0
      DO 80 L=1,N
   80 C(1)=C(1)+D0(L)-A(L)
C
C        CALL SUBROUTINES TO SOLVE THE SYSTEM OF LINEAR EQUATIONS BY GAUSSIAN
C        ELIMINATION.  IF A SINGULAR MATRIX IS FOUND, STOP EXECUTION.
C
   81 CALL DECOMP(K0,B,UL,KS)
      IF(KS.GT.0) STOP
      CALL SOLVE(K0,UL,C,GX)
C
C        STORE OPTIMUM VALUES FOR THE PARAMETERS IN G.
C
      DO 400 J=1,K0
  400 G(J)=GX(J)
      G(1)=G(1)/2.0
      RETURN
      END
```

```
      SUBROUTINE COMPAR
C
C        SUBROUTINE COMPAR CALCULATES PREDICTED CONCENTRATIONS USING THE
C        EQUATION FOR DOWNSTREAM CONCENTRATION.  ERROR IN CALCULATION IS
C        EXPRESSED AS THE SUM OF SQUARED ERRORS BETWEEN OBSERVED AND
C        CALCULATED DOWNSTREAM CONCENTRATIONS.
C
      COMMON AK
      COMMON M,DT
      COMMON START, ZCOS(50,100),ZSIN(50,100),CSI(100)
      COMMON K0,Z
      COMMON D0(100),U(100),G(50)
      COMMON D,N,W,D1,S,K
      COMMON/AL/AL1,AL2,AL3,AL4,AL5,KODE
      COMMON/PR/PROD(100),UPROD(100),DPROD(100),QPROD(100)
      DIMENSION C(50)
      CHARACTER*10 AL1,AL2,AL3,AL4,AL5
      DO 402 J=1,K0
  402 C(J)=G(J)
      Z=0
C
C        CALCULATE AND STORE PARTS OF THE EQUATION
C
      DO 90 L=1,N
      L0=L+M-1
      AL=L
      T1=D1*(AL-1.0)*W
      T2=T1+D*W
      R1=S*U(L)+(C(1)/AK)*(1.0-S)+CSI(L)
      R2=0
      DO 50 IS=2,K0
      V=IS-1
      IV=IS-1
      W1=C(IS)/(AK**2+(V*W)**2)
      W2=AK*ZCOS(IV,L0)+V*W*ZSIN(IV,L0)-S*(AK*ZCOS(IV,L)+V*W*ZSIN(IV,L))
   50 R2=R2+W1*W2
C
C        CALCULATE CONCENTRATION AND TIME
C
   60 R=R1+R2
      T3=T2/W
      TIME=T3+START
      GO TO 88
   88 IF(TIME.GT.24.0) GO TO 89
C
C        PRINT TIME AND CALCULATED AND OBSERVED VALUES
C
      PRINT 1070,TIME,R,D0(L)
 1070 FORMAT(1H ,F6.2,3X,E14.7,6X,E14.7)
      GO TO 90
   89 TIME=TIME-24.0
      GO TO 88
```

```
C
C         CALCULATE AND PRINT SUM OF SQUARED ERRORS
C
   90 Z=Z+(R-DO(L))**2
   75 PRINT 1080,Z
 1080 FORMAT(1H0,22HSUM OF SQUARED ERRORS=,E14.7)
      PRINT 1090
 1090 FORMAT(1H0,4HTIME,5X,3HP-R)
      NQ=N+M-1
      DO 110 J=1,NQ
      T=J
      T=(T-1.0)*D1
      Y=C(1)
C
C         CALCULATE AND PRINT GROSS PRODUCTION
C
      DO 100 IS=2,KO
      Q=IS-1
  100 Y=Y+C(IS)*COS(Q*W*T)
      QPROD(J)=Y
      IF(KODE.LT.3) PROD(J)=Y
      IF(KODE.EQ.3)   UPROD(J)=Y
      IF(KODE.EQ.4)   DPROD(J)=Y
      TIME=T+START
  108 IF(TIME.GT.24.0) GO TO 109
      PRINT 1100,TIME,Y
 1100 FORMAT(1H ,F6.2,3X,E15.8)
      GO TO 110
  109 TIME=TIME-24.0
      GO TO 108
  110 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DECOMP(NN,A,UL,KS)
C
C        SUBROUTINE DECOMP PERFORMS A TRIANGULAR DECOMPOSITION OF MATRIX
C        A. DIVIDING IT INTO AN UPPER AND LOWER TRIANGULAR MATRIX,THE SYSTEM
C        A*X=B MAY THEN BE WRITTEN L*U*X=B, WHICH IS SOLVED IN SUBROUTINE
C        SOLVE.
C
      DIMENSION A(50,50),UL(50,50),SCALES(50),IPS(50)
      COMMON/EQ/IPS
      N=NN
      KS=0
      DO 5 I=1,N
      IPS(I)=I
      ROWNRM=0.0
      DO 2 J=1,N
      UL(I,J)=A(I,J)
      IF(ROWNRM-ABS(UL(I,J))) 1,2,2
    1 ROWNRM=ABS(UL(I,J))
    2 CONTINUE
      IF(ROWNRM) 3,4,3
    3 SCALES(I)=1.0/ROWNRM
      GO TO 5
    4 CALL SING(1)
      KS=1
      SCALES(I)=0.0
    5 CONTINUE
      NM1=N-1
      DO 17 K=1,NM1
      BIG=0.0
      DO 11 I=K,N
      IP=IPS(I)
      SIZE=ABS(UL(IP,K))*SCALES(IP)
      IF(SIZE-BIG) 11,11,10
   10 BIG=SIZE
      IDXPIV=I
   11 CONTINUE
      IF(BIG) 13,12,13
   12 CALL SING(2)
      KS=2
      GO TO 17
   13 IF(IDXPIV-K) 14,15,14
   14 J=IPS(K)
      IPS(K)=IPS(IDXPIV)
      IPS(IDXPIV)=J
   15 KP=IPS(K)
      PIVOT=UL(KP,K)
      KP1=K+1
      DO 16 I=KP1,N
      IP=IPS(I)
      EM=-UL(IP,K)/PIVOT
      UL(IP,K)=-EM
      DO 16 J=KP1,N
      UL(IP,J)=UL(IP,J)+EM*UL(KP,J)
   16 CONTINUE
   17 CONTINUE
      KP=IPS(N)
      IF(UL(KP,N)) 19,18,19
   18 CALL SING(2)
      KS=2
   19 RETURN
      END
```

```
      SUBROUTINE SOLVE(NN,UL,B,X)
C
C        THIS SUBROUTINE SOLVES THE TWO SYSTEMS L*Y=B AND U*X=Y TO FIND
C        MATRIX X.
C
      DIMENSION UL(50,50),B(50),X(50),IPS(50)
      COMMON/EQ/IPS
      N=NN
      NP1=N+1
      IP=IPS(1)
      X(1)=B(IP)
C
C        FORWARD ELIMINATION
C
      DO 2 I=2,N
      IP=IPS(I)
      IM1=I-1
      SUM=0.0
      DO 1 J=1,IM1
    1 SUM=SUM+UL(IP,J)*X(J)
    2 X(I)=B(IP)-SUM
      IP=IPS(N)
      X(N)=X(N)/UL(IP,N)
C
C        BACK SUBSTITUTION
C
      DO 4 IBACK=2,N
      I=NP1-IBACK
      IP=IPS(I)
      IP1=I+1
      SUM=0.0
      DO 3 J=IP1,N
    3 SUM=SUM+UL(IP,J)*X(J)
    4 X(I)=(X(I)-SUM)/UL(IP,I)
      RETURN
      END
```

```
      SUBROUTINE SING(IWHY)
C
C        THIS SUBROUTINE PRINTS DIAGNOSTICS IF A SINGULAR MATRIX IS
C        FOUND IN DECOMP
C
      IF(IWHY.EQ.2) GO TO 2
      PRINT 11
   11 FORMAT(1H0,33HMATRIX WITH ZERO ROW IN DECOMPOSE)
      RETURN
    2 PRINT 12
   12 FORMAT(1H0,51HSINGULAR MATRIX IN DECOMPOSE, ZERO DIVIDE IN SOLVE.)
      RETURN
      END
```

```
      SUBROUTINE PLOT(MPT,VAL,IX,XVAL,CPLOT)
C
C        THIS SUBROUTINE PLOTS OXYGEN PRODUCTION AGAINST TIME.
C
      COMMON AK
      COMMON M,DT
      COMMON START,ZCOS(50,100),ZSIN(50,100),CSI(100)
      COMMON/PT/P(5),VMAX,VMIN
      DIMENSION VAL(MPT),CLEAN(5),LINE(101)
      INTEGER CLEAN,LINE,P,DOT,BLANK,STAR
      DATA DOT,BLANK,STAR/1H.,1H ,1H*/
      DATA P(1)/1HP/
      TS4V=CPLOT
      X=IX
      CPLOT=CPLOT*X
      XVAL=6.0*CPLOT
      VMAX=-1000.
      VMIN=1000.
C
C        CALCULATE MAXIMUM AND MINIMUM PRODUCTION VALUES
C
      DO 50 I=1,MPT,IX
      IF(VAL(I).GT.VMAX) VMAX=VAL(I)
      IF(VAL(I).LT.VMIN) VMIN=VAL(I)
   50 CONTINUE
      XFACT=0.0
      XVALC=-CPLOT
C
C        PRINT TITLE
C
      PRINT 100
  100 FORMAT(1H0,25X,54HNET PRODUCTIVITY,GRAMS OXYGEN PER CUBIC METER PE
     +R HOUR)
      KPL=2
C
C        SCALE AND PRINT PRODUCTION AXIS
C
      IF(VMAX.LT.1.5.AND.VMIN.GT.-1.0) GO TO 60
      VMIN=-2.0
      VMAX=3.0
      PRINT 102
  102 FORMAT(1H ,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=1
      PRINT 101
  101 FORMAT(1H ,15X,4H-1.0,14X,4H-0.5,16X,3H0.0,16X,3H0.5,17X,3H1.0,
     117X,3H1.5)
   70 DO 110 J=1,101
      LINE(J)=DOT
      M=MOD(J-1,20)
      IF(M.EQ.0) LINE(J)=STAR
```

```
  110 CONTINUE
      PRINT 103,LINE
  103 FORMAT(15X,101A1)
      DO 111 J=1,101
  111 LINE(J)=BLANK
      LINE(41)=DOT
      Z=0.
C
C         STORE PRODUCTION VALUE FOR EACH TIME
C
      DO 116 K=1,MPT,IX
      XVALC=XVALC+CPLOT
      IF(VAL(K).GT.VMAX) VAL(K)=VMAX
      IF(VAL(K).LT.VMIN) VAL(K)=VMIN
      J=100.0*(0.4*(VAL(K)+1))+1.5
      IF(KPL.EQ.2) J=100.0*((0.6/VMAX)*VAL(K)+0.4)*1.5
      IF(J.EQ.41) Z=10.
      LINE(J)=P(1)
      CLEAN(1)=J
      IF(ABS(XVAL-XVALC).GT.0.001) GO TO 113
      XFACT=XFACT+1.0
      IF(Z.EQ.0.) LINE(41)=STAR
      Z=0.
      XVALC=0.
      X=XFACT*XVAL+START
   80 IF(X.GT.24.0) GO TO 90
      IF(XVAL.LT.1) GO TO 81
C
C         PRINT POINTS
C
      PRINT 104,X,LINE
  104 FORMAT(4X,F5.0,6H00 HRS,101A1)
      GO TO 114
   81 PRINT 105,X,LINE
  105 FORMAT(4X,F5.2,1X,3HHRS,1X,101A1)
      GO TO 114
   90 X=X-24.0
      GO TO 80
  113 PRINT 103,LINE
  114 ICLEAN=CLEAN(1)
      LINE(ICLEAN)=BLANK
      LINE(41)=DOT
  116 CONTINUE
      CPLOT=TSAV
      RETURN
      END
```

```
      SUBROUTINE OXYPLOT(MPT,X1,X2,XVAL,CPLOT,VMIN,VMAX,IX)
C
C        THIS SUBROUTINE PLOTS OXYGEN CONCENTRATION AGAINST TIME
C
      COMMON AK
      COMMON M,DT
      COMMON START,ZCOS(50,100),ZSIN(50,100),CSI(100)
      DIMENSION X1(MPT),X2(MPT),CLEAN(2),LINE(101),P(2),Y(5)
      INTEGER CLEAN,LINE,P,DOT,BLANK,STAR
      DATA DOT,BLANK,STAR/1H.,1H ,1H*/
      DATA P(1),P(2)/1H0,1HS/
      CHARACTER*1 JRJ
      EQUIVALENCE(JRJ,IDEN)
      JRJ=1H0
      TSAV=CPLOT
      X=IX
      CPLOT=X*CPLOT
      XVAL=6.0*CPLOT
      VMINS=VMIN
      VMAXS=VMAX
      IMIN=INT(VMIN)
      IMAX=INT(VMAX+1.0)
      VMIN=IMIN
      VMAX=IMAX
C
C        SCALE CONCENTRATION AXIS
C
      DY=(VMAX-VMIN)/5.0
      Y(1)=VMIN
      DO 11 I=2,6
   11 Y(I)=Y(I-1)+DY
      XVALC=0.0
      XFACT=0.0
      XVALC=-CPLOT
      PRINT 100
  100 FORMAT(1H0,35X,42HOXYGEN CONCENTRATION,GRAMS PER CUBIC METER)
C
C        PRINT CONCENTRATION AXIS
C
      PRINT 101,Y(1),Y(2),Y(3),Y(4),Y(5),Y(6)
  101 FORMAT(12X,6(F5.1,15X))
      DO 110 J=1,101
      LINE(J)=DOT
      M=MOD(J-1,20)
      IF(M.EQ.0) LINE(J)=STAR
  110 CONTINUE
      PRINT 103,LINE
  103 FORMAT(15X,101A1)
      DO 111 J=2,101
  111 LINE(J)=BLANK
      LINE(1)=DOT
C
```

```
C          STORE CONCENTRATION VALUES FOR EACH TIME
C
      DO 116 K=1,MPT,IX
      XVALC=XVALC+CPLOT
      J=(100.0/(VMAX-VMIN))*(X1(K)-VMIN)+1.5
      LINE(J)=IDEN
      CLEAN(1)=J
      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+1.0
      LINE(1)=STAR
      XVALC=0.
      X=XFACT*XVAL+START
   80 IF(X.GT.24.0) GO TO 90
      IF(XVAL.LT.1) GO TO 81
C
C          PRINT CONCENTRATION VALUES
C
      PRINT 104,X,LINE
  104 FORMAT(3X,F5.0,6H08 HRS,1X,101A1)
      GO TO 114
   81 PRINT 105,X,LINE
  105 FORMAT(3X,F5.2,1X,3HHRS,1X,101A1)
      GO TO 114
   90 X=X-24.0
      GO TO 80
  113 PRINT 103,LINE
  114 DO 115 L=1,2
      ICLEAN=CLEAN(L)
      LINE(ICLEAN)=BLANK
  115 CONTINUE
      LINE(1)=DOT
  116 CONTINUE
      VMIN=VMINS
      VMAX=VMAXS
      CPLOT=TSAV
      RETURN
      END
```

```
      SUBROUTINE RADPLT(N,P,R,START,DT)
C
C        THIS SUBROUTINE PLOTS NET PRODUCTIVITY AGAINST RADIATION
C
      COMMON/T/THRS
      DIMENSION PS(100),RS(100)
      DIMENSION P(N),R(N),LINE(101),POINT(20),M(20),YP(10),T(15)
      INTEGER CLEAN,LINE,DOT,BLANK,STAR,Y,T
      DATA DOT,BLANK,STAR/1H.,1H ,1H*/
      INTEGER W
      DATA W/1HW/
      DATA Y/1HX/
      DATA T(1),T(2),T(3),T(4),T(5)/1HA,1HB,1HC,1HD,1HE/
      DATA T(6),T(7),T(8),T(9),T(10)/1HF,1HG,1HH,1HI,1HJ/
      DATA T(11),T(12),T(13),T(14),T(15)/1HK,1HL,1HM,1HN,1HO/
      IMIN=(6.0-START)/DT+1.1
      IMAX=(20.0-START)/DT+1.1
      IS=1
C
C        CALCULATE MAXIMUM VALUES FOR PRODUCTION AND RADIATION
C
      RMAX=-1000.
      PMAX=-1000.
      PMIN=1000.
      DO 10 I=1,N
      IF(R(I).GT.RMAX) RMAX=R(I)
      IF(P(I).GT.PMAX) PMAX=P(I)
      IF(P(I).LT.PMIN) PMIN=P(I)
   10 CONTINUE
      IF(RMAX.LE..5) DX=.01
      IF(RMAX.GT.0.5.AND.RMAX.LE.1.0) DX=.02
      IF(RMAX.GT.1.0.AND.RMAX.LE.1.5) DX=.03
      IF(RMAX.GT.1.5) DX=.04
      XVAL=3.0*DX
      XVALC=-DX
      XFACT=0.0
C
C        PRINT TITLES
C
      PRINT 105
  105 FORMAT(1H1,33HNET PRODUCTIVITY VERSUS RADIATION)
      PRINT 106
  106 FORMAT(1H0,35X,55HNET PRODUCTIVITY, GRAMS OXYGEN PER CUBIC METER P
     +ER HOUR)
C
C        SCALE PRODUCTION AXIS
C
      YP(1)=-INT(10.0*ABS(PMIN)+1.0)
      YP(1)=YP(1)/10.0
      PMIN=YP(1)
      PMAX=INT(10.0*PMAX+1.0)
      PMAX=PMAX/10.0
```

```
      DY=(PMAX-YP(1))/5.0
      DO 15 I=2,6
   15 YP(I)=YP(I-1)+DY
C
C        PRINT PRODUCTION AXIS
C
      PRINT 101,YP(1),YP(2),YP(3),YP(4),YP(5),YP(6)
  101 FORMAT(12X,6(F5.2,15X))
      DO 20 J=1,101
      LINE(J)=DOT
      MM=MOD(J-1,20)
      IF(MM.EQ.0) LINE(J)=STAR
   20 CONTINUE
      PRINT 103,LINE
  103 FORMAT(15X,101A1)
      DO 25 J=1,101
   25 LINE(J)=BLANK
C
C        CALCULATE POINTS AND STORE VALUES
C
      DO 100 J=1,50
      X=(J-1)*DX
      XP=X+DX/2.0
      XM=X-DX/2.0
      XVALC=XVALC+DX
      K=0
      DO 50 I=1,N
      IF(R(I).LE.THRS)   GO TO 50
      IF(R(I).LT.XM.OR.R(I).GE.XP) GO TO 50
      POINT(K+1)=P(I)
      M(K+1)=I
      K=K+1
      PS(IS)=P(I)
      RS(IS)=R(I)
      IS=IS+1
   50 CONTINUE
      KK=K
      IF(K.EQ.0) GO TO 75
      IPS=-1
   55 YMIN=1000.
      DO 60 I=1,K
      IF(POINT(I).GT.YMIN) GO TO 60
      YMIN=POINT(I)
      II=I
   60 CONTINUE
      POINT(II)=10000.0
      KK=KK-1
      IP=(100.0/(PMAX-PMIN))*(YMIN-PMIN)+1.5
      LINE(IP)=Y
      IF(M(II).LT.IMIN.OR.M(II).GT.IMAX) GO TO 71
      ITIM=FLOAT(M(II)-IMIN)*DT+1.1
      LINE(IP)=T(ITIM)
```

```
      IF(IP.EQ.IPS) LINE(IP)=W
      IPS=IP
   71 IF(KK.EQ.0) GO TO 75
      GO TO 55
   75 IF(ABS(XVALC-XVAL).GT.0.0000001) GO TO 90
      XFACT=XFACT+1.0
      LINE(1)=STAR
      XVALC=0.
      XPLOT=XFACT*XVAL
  201 FORMAT(1H+,97X,14HA-0600 TO 0659)
  202 FORMAT(1H+,97X,14HB-0700 TO 0759)
  203 FORMAT(1H+,97X,14HC-0800 TO 0849)
  204 FORMAT(1H+,97X,14HD-0900 TO 0959)
  205 FORMAT(1H+,97X,14HE-1000 TO 1059)
  206 FORMAT(1H+,97X,14HF-1100 TO 1159)
  207 FORMAT(1H+,97X,14HG-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,19HW-COINCIDING POINTS)
C
C        PRINT RADIATION AXIS AND POINTS
C
      PRINT 104,XPLOT,LINE
  104 FORMAT(3X,F5.2,1X,3HLYS,3X,101A1)
      IF(J.EQ.4)  PRINT 203
      IF(J.EQ.7)  PRINT 206
      IF(J.EQ.10)  PRINT 209
      IF(J.EQ.13)  PRINT 212
      IF(J.EQ.16)  PRINT 215
      GO TO 95
   90 PRINT 103,LINE
      IF(J.EQ.2)  PRINT 201
      IF(J.EQ.3)  PRINT 202
      IF(J.EQ.5)  PRINT 204
      IF(J.EQ.6)  PRINT 205
      IF(J.EQ.8)  PRINT 207
      IF(J.EQ.9)  PRINT 208
      IF(J.EQ.11)  PRINT 210
      IF(J.EQ.12)  PRINT 211
      IF(J.EQ.14)  PRINT 213
      IF(J.EQ.15)  PRINT 214
      IF(J.EQ.17)  PRINT 216
   95 DO 96 I=1,101
   96 LINE(I)=BLANK
      LINE(I)=DOT
  100 CONTINUE
```

```
      SQRY=0.0
      SQR=0.0
      PROD=0.0
      SUMY=0.0
      SUMX=0.0
      ISM=IS-1
C
C        CALCULATE AND PRINT SLOPE, INTERCEPT AND CORRELATION COEFFICIENT
C
      DO 1050 I=1,ISM
      SUMX=SUMX+RS(I)
      SUMY=SUMY+PS(I)
      SQR=SQR+RS(I)**2
      SQRY=SQRY+PS(I)**2
 1050 PROD=PROD+RS(I)*PS(I)
      XN=ISM
      COF=(PROD-SUMX*SUMY/XN)/(((SQR-SUMX**2/XN)*(SQRY-SUMY**2/XN))**.5)
      A1=(XN*PROD-SUMX*SUMY)/(XN*SQR-SUMX**2)
      A0=(SUMY-A1*SUMX)/XN
      PRINT 150,A0,A1,COF
  150 FORMAT(1H0,10HINTERCEPT-,F7.3,3X,6HSLOPE=,F7.4,3X,24HCORRELATION C
     +OEFFICIENT=,F6.3)
      P(1)=A1
      P(2)=A0
      P(3)=COF
      RETURN
      END
```

Table A1

Definitions of FORTRAN Variables

FORTRAN Identifier	Definitions
AL1,AL2,AL3,AL4,AL5	Alphanumeric problem identifiers (e.g. date)
AK	Reaeration coefficient
D	Residence time
DO	Downstream oxygen concentrations
DRAD	Downstream radiation
DS	Downstream temperature
DT	Data sampling interval
F1	Time of sunrise
F2	Time of sunset
KO	Number of Fourier coefficients
KRAD	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
KODE	Operation code = 2 for two station method, = 3 for single station upstream, = 4 for single station downstream, = 1 for all of the above
N	Number of data points
NUMB	Number of days of data to process
PRES	Atmospheric pressure in millibars corrected to sea level
START	Starting time
THRS	Threshold value of radiation below which radiation is considered zero
U	Upstream oxygen concentrations
URAD	Upstream radiation
US	Upstream temperature

Table A2

Cards For Input to Flowing Water Program

Card Number	Variables	Format
1	NUMB	I2
2	AL1,AL2,AL3,AL4,AL5	5A10
3	KODE,KRAD,THRS	2I2,F10
4	D,DT,PRES,N,KO	3F10,2I5
5	AK,START	2F10
6 through N+5	US(I),U(I),URAD(I)	Free field
N+5 through 2N+5	DS(I),DO(I),DRAD(I)	Free field
2N+6	F1,F2	2F10

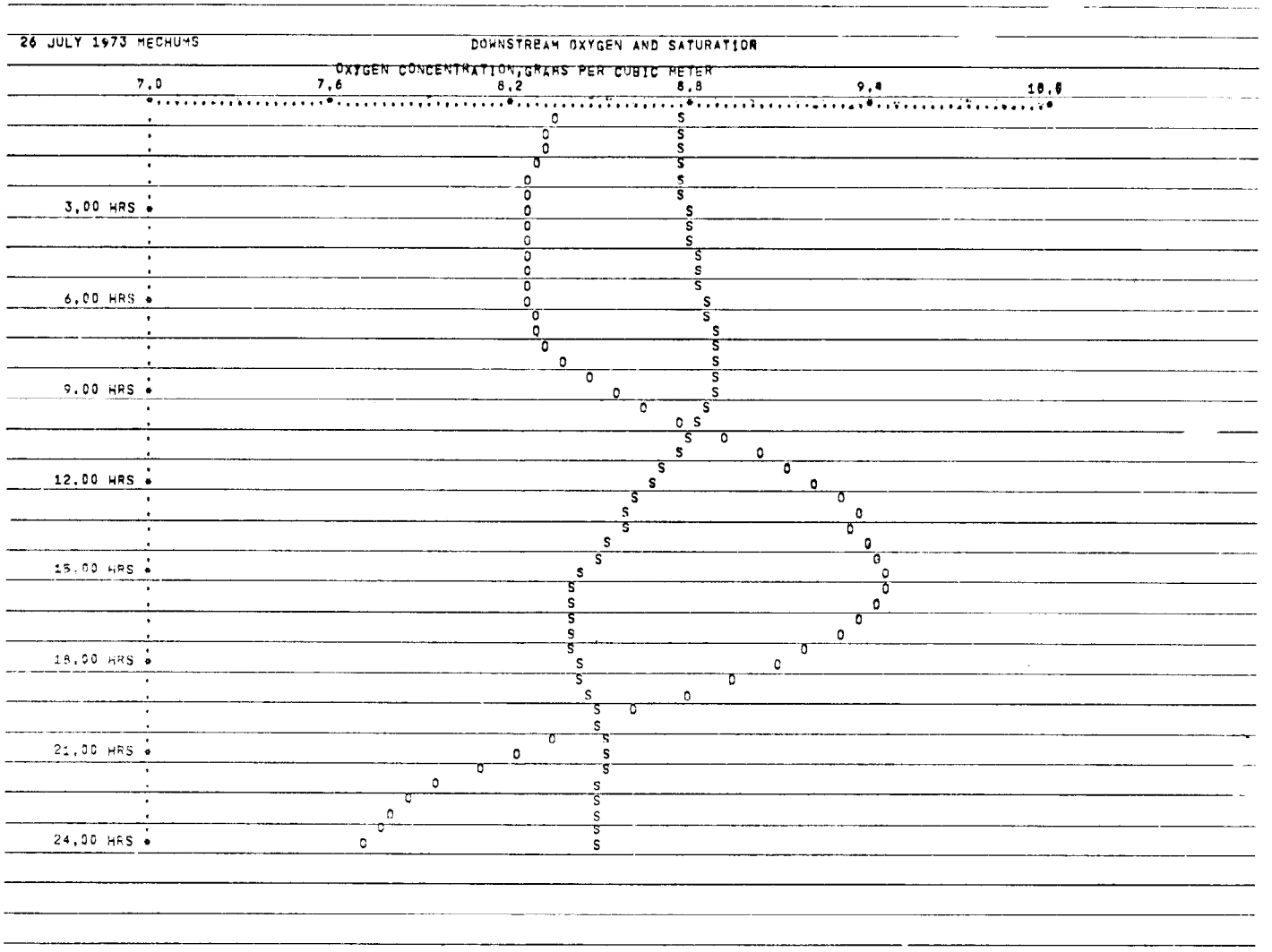

Figure A1. Typical output from flowing water program (sheet 1 of 3)

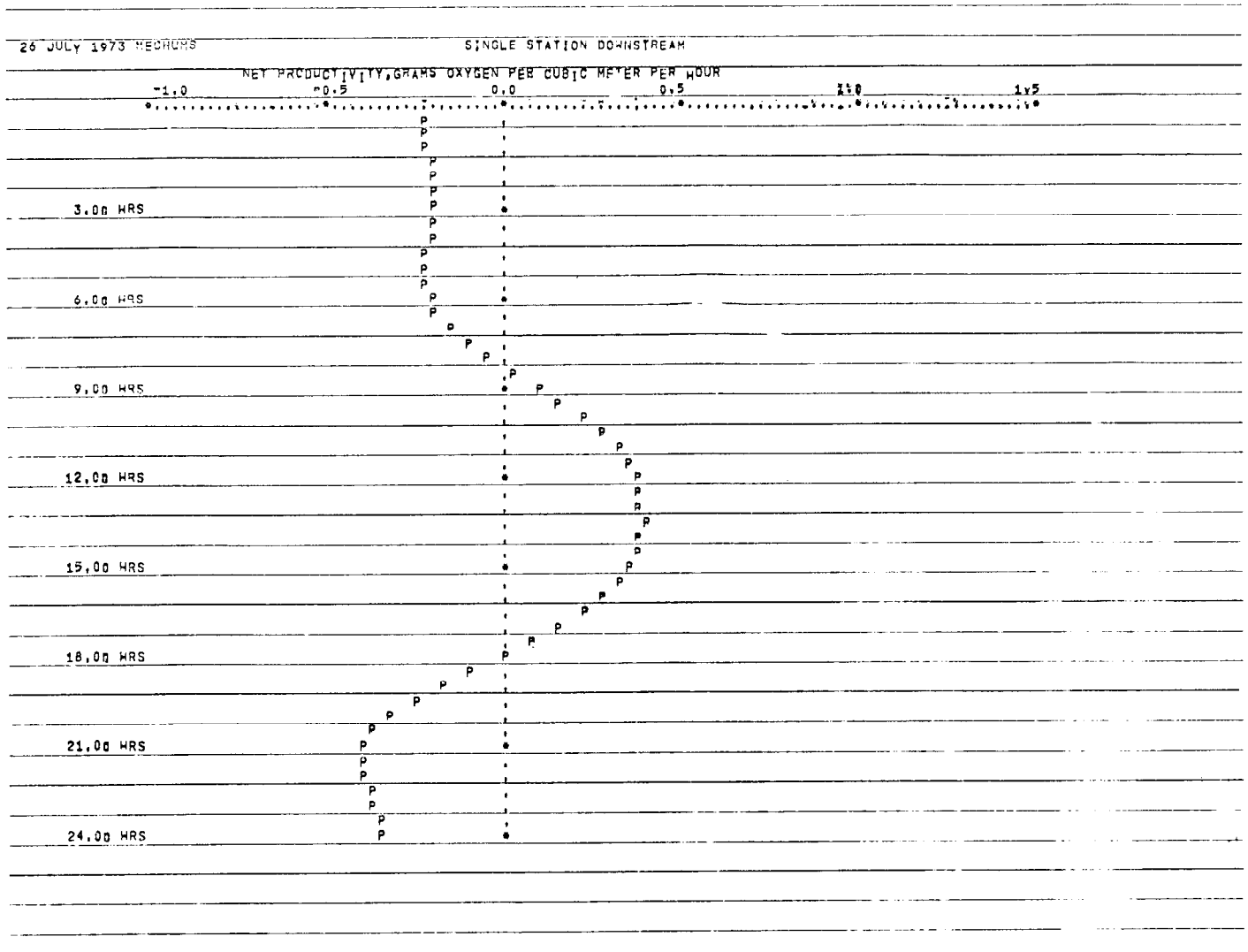

Figure A1. (sheet 2 of 3)

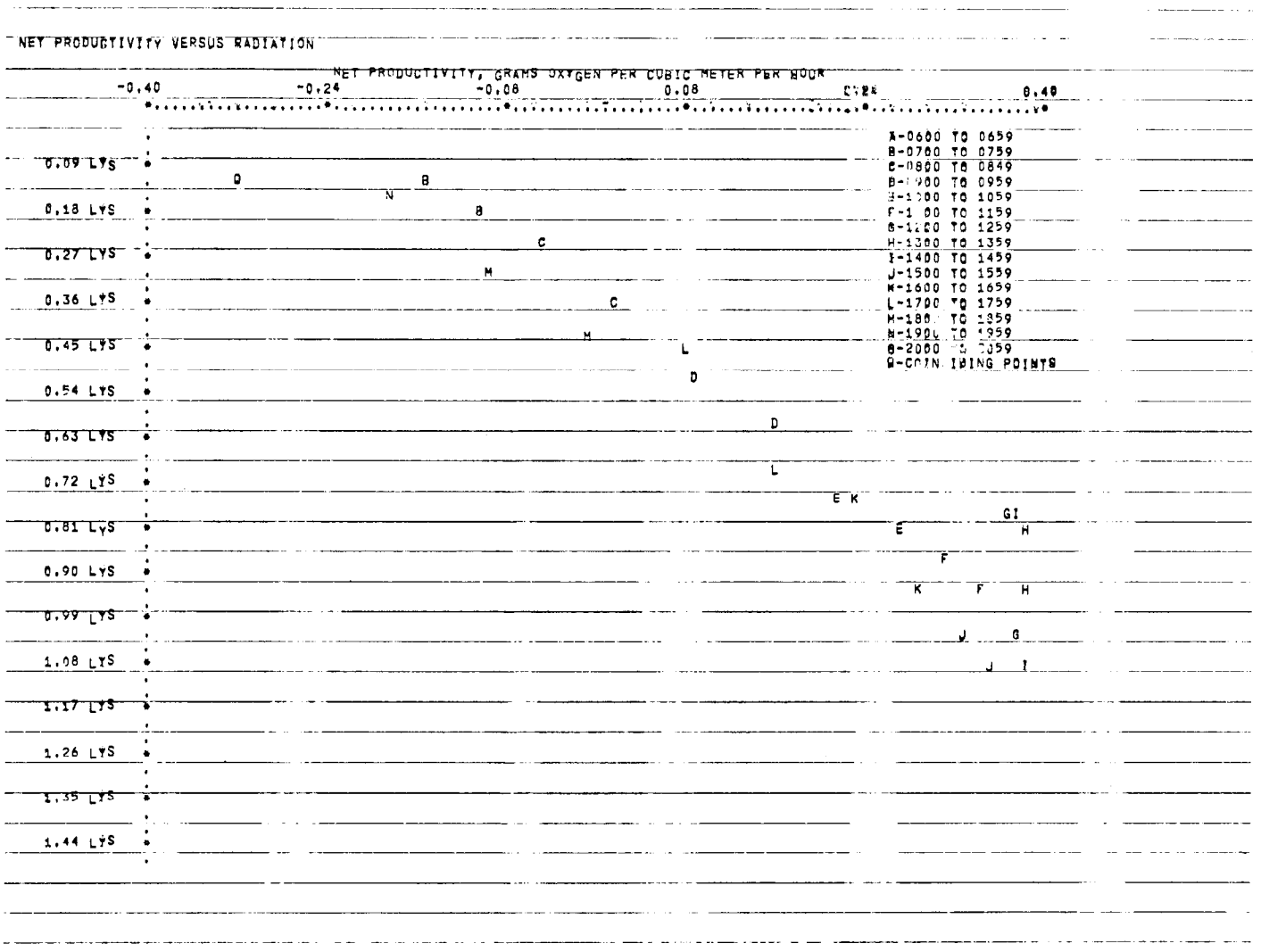

Figure A1. (sheet 3 of 3)

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.

```
C
C       THIS PROGRAM CALCULATES RATES OF PHOTOSYNTHESIS AND RESPIRATION
C       IN A RIVER COMMUNITY USING A METHOD DEVELOPED BY MAHLON G. KELLY,
C       GEORGE M. HORNBERGER, AND B. J. COSBY AT THE DEPARTMENT OF ENV
C       IRONMENTAL SCIENCES, UNIVERSITY OF VIRGINIA, CHARLOTTESVILLE,
C       VIRGINIA.  THE PROGRAM WAS WRITTEN BY GEORGE M. HORNBERGER AND
C       VIRGINIA HENDRY OF THAT DEPARTMENT.  THE SUBROUTINES DECOMP,
C       SOLVE AND SING WERE COPIED, WITH SLIGHT MODIFICATIONS, FROM  COMPUTER
C       SOLUTION OF LINEAR ALGEBRAIC SYSTEMS BY GEORGE E. FORSYTHE AND
C       CLEVE B. MOLER (PRENTICE-HALL, 1967).
C
C
C       METHOD
C
C            MODIFICATION FOR STANDING WATERS-AVERAGE OXYGEN BUDGET.
C            THE MASS BALANCE EQUATION FOR OXYGEN IN STANDING WATER MAY
C            BE REPRESENTED BY THE EQUATION
C
C                 DCBAR/DT=K*(CS-CSURF) + (P-R)
C
C            WHERE CBAR = AVERAGE CONCENTRATION (ENTIRE WATER BODY)
C                  CS   = SATURATION CONCENTRATION (SURFACE)
C                  CSURF= SURFACE CONCENTRATION
C                  K    = REAERATION COEFFICIENT
C                  P-R  = NET PRODUCTIVITY
C
C            NET PRODUCTIVITY MAY BE REPRESENTED BY A FOURIER SERIES
C
C                 P-R = A0/2 + SUM FROM N=1 TO K0 OF (AN*COS(N*W*T))
C
C            WHERE AN = COEFFICIENTS
C                  W  = PI/PERIOD OF OBSERVATION
C                  T  = TIME
C
C            THE DIFFERENTIAL EQUATION MAY BE SOLVED USING KNOWN
C            SURFACE VALUES AND THE PREDICTED VALUES OF CBAR MAY
C            BE COMPARED WITH OBSERVED VALUES.
C
      COMMON/AL/AL1,AL2,AL3,AL4,AL5
      COMMON/A/AK,DT,K0,Z,N,W,KT,DEPTH
      COMMON/B/START,YSIN(50,100),UI(100),QPROD(100)
      COMMON/C/G(50),CAVG(100),CSURF(100),CS(100),TIM(100)
      COMMON/T/THRS
      DIMENSION RAD(100),TEMP(100)
      DIMENSION CDIF(100)
      DIMENSION IFOR(3)
      REAL MATO(100)
      CHARACTER*10 AL1,AL2,AL3,AL4,AL5
C
C     READ IN NUMBER OF DAYS TO RUN
C
      READ 19,NUMB
```

```
   19 FORMAT(I2)
      NCHK=0
C
C        READ IN ALPHANUMERIC CHARACTERS FOR LOCATION AND DATE
C
 9000 READ 5000,AL1,AL2,AL3,AL4,AL5
 5000 FORMAT(5A10)
C
C        READ IN DATA MODE INFORMATION
C
C              KRAD=0  NO RADIATION DATA AVAILABLE
C                   =1  RADIATION MEASURED
C
C             THRS=THRESHOLD VALUE OF RADIATION
C
      READ 20,KRAD,THRS
   20 FORMAT(I2,F10.0)
C
C       READ IN SAL=SALINITY(MILLIGRAMS/LITER CL)
C                DT=DATA INTERVAL(HOURS)
C              PRES=ATMOSPHERIC PRESSURE(MILLIBARS, CORRECTED TO SEA LEVEL)
C                 N=NUMBER OF DATA POINTS
C                KO=NUMBER OF PARAMETERS
C
      READ 5,SAL,DT,PRES,N,KO
    5 FORMAT(I6,2F10.0,2I5)
C
C        READ IN     AK=REAERATION COEFFICIENT(METERS/HOUR)
C                 START=STARTING TIME(HOURS)
C
      READ 10,AK,START
   10 FORMAT(2F10.0)
C
C        READ IN DEPTH (METERS)
C
      READ 910,DEPTH
  910 FORMAT(F5.2)
C
C        INITIALIZE ARRAYS
C
      DO 600 I=1,N
      TIM(I)=0.0
      CAVG(I)=0.0
      CSURF(I)=0.0
      TEMP(I)=0.0
  600 RAD(I)=0.0
C
      IF(KRAD.GT.0)  GO TO 605
C
C        READ IN OXYGEN DATA
C
C             TIM=TIME(HOURS)
```

```
C            CAVG=AVERAGE CONCENTRATION(GRAMS/CUBIC METER)
C           CSURF=SURFACE CONCENTRATION(GRAMS/CUBIC METER)
C            TEMP=SURFACE TEMPERATURE(DEGREES CENTIGRADE)
C             RAD=RADIATION(LANGLEYS)
C
 6100 FORMAT(V)
      M=2
      DO 601 I=1,N
  601 READ 6100,TIM(I),CAVG(I),CSURF(I),TEMP(I)
      GO TO 3
  605 DO 606 I=1,N
  606 READ 6100,TIM(I),CAVG(I),CSURF(I),TEMP(I),RAD(I)
    3 IF(KRAD.NE.0) GO TO 2
C
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)
      I1=F1/DT+1.0
      I2=F2/DT+1.0
    2 KT=24.0/DT+1.0
      DAY=TIM(N)-TIM(1)
      W=6.28318/(2.0*DAY)
      VMIN=1000.
      VMAX=0.
      DO 912 I=1,N
      IF(CAVG(I).LT.VMIN)  VMIN=CAVG(I)
      IF(CAVG(I).GT.VMAX)  VMAX=CAVG(I)
  912 IF(CS(I).GT.VMAX)  VMAX=CS(I)
      PRINT 6000
 6000 FORMAT(1H1,50H**************************************************)
      CORR=PRES/1013.25
C
C        CONVERT TEMPERATURE TO SATURATION CONCENTRATION OF OXYGEN
C
  619 DO 70 I=1,N
      CALL SATURAT(CS(I),TEMP(I),SAL)
C
C        CORRECT SATURATION FOR ATMOSPHERIC PRESSURE
C
      CS(I)=CS(I)*CORR
   70 CONTINUE
C
C        CALCULATE THE INTEGRAL OF RADIATION OVER THE INTERVAL FROM SUNRISE
C          TO SUNSET, USING THE TRAPEZOIDAL RULE
C
      RINT=0.0
      IF(RAD(1).GT.THRS) GO TO 750
      IF(KRAD.EQ.0) GO TO 750
      I1=10000
      DO 740 I=1,N
```

```
      DX=TIM(I)-TIM(I-1)
      IF(I.EQ.1)   DX=TIM(1)
      IF(RAD(I).LE.THRS) GO TO 730
      IF(I1.GT.I) I1=I-1
      RINT=(RAD(I-1)+RAD(I))*DX+RINT
      I2=I+1
      GO TO 740
  730 IF(I.EQ.1) GO TO 740
      IF(RAD(I-1).LE.THRS) GO TO 740
      RINT=RINT+(RAD(I-1)+RAD(I))*DX
  740 CONTINUE
      IF(I1.EQ.0) I1=1
      RINT=RINT*60.0/2.0
      IF(RINT.EQ.0) KRAD=0
  750 CONTINUE
C
C         PRINT HEADINGS
C
      PRINT 1041,AK,K0
 1041 FORMAT(1H ,50X,13HREAER. COEF.-,F6.3,5X,11HPARAMETERS-,I2)
      PRINT 5001,AL1,AL2,AL3,AL4,AL5
 5001 FORMAT(1H ,5A10)
      PRINT 1040
 1040 FORMAT(1H0,50H**************************************************)
      PRINT 975
  975 FORMAT(1H0,17X,7HAVERAGE,8X,7HSURFACE,8X,10HSATURATION)
      IF(KRAD.NE.0) GO TO 948
      PRINT 980
  980 FORMAT(1H ,11X,4HTIME,3(2X,13HCONCENTRATION))
      GO TO 949
  948 PRINT 985
  985 FORMAT(1H ,11X,4HTIME,3(2X,13HCONCENTRATION),6X,9HRADIATION)
C
C         PRINT CONCENTRATION DATA AND TIME
C
  949 DO 950 I=1,N
      IF(KRAD.NE.0) GO TO 9500
      PRINT 1005,TIM(I),CAVG(I),CSURF(I),CS(I)
 1005 FORMAT(1H ,4F15.4)
      GO TO 950
 9500 PRINT 1006,TIM(I),CAVG(I),CSURF(I),CS(I),RAD(I)
 1006 FORMAT(1H ,5F15.4)
  950 CONTINUE
C
C         PRINT HEADINGS
C
      PRINT 1070
 1070 FORMAT(1H1,10X,16HNET PRODUCTIVITY)
      PRINT 1040
      PRINT 5001,AL1,AL2,AL3,AL4,AL5
      PRINT 1040
      PRINT 1100
```

```
 1100 FORMAT(1H0,1X,9HNO. VALS.,5X,5HREAER,5X,5HPRES.)
      PRINT 1110,N,AK,PRES
 1110 FORMAT(1H ,8X,I2,5X,F5.2,2X,F8.2)
C
C         CALCULATE PARTS OF THE EQUATION FOR DOWNSTREAM CONCENTRATIONS
C         AND STORE FOR CONVENIENCE.
C
      DO 901 I=1,K0
      DO 901 J=1,N
  901 YSIN(I,J)=SIN(I*W*TIM(J))
      DO 902 I=1,N
  902 CDIF(I)=CS(I)-CSURF(I)
      DO 904 J=1,N
      UI(J)=0.0
      DO 904 I=2,J
  904 UI(J)=UI(J)+(CDIF(I)+CDIF(I-1))*(TIM(I)-TIM(I-1))/2.0
      DO 905 J=1,N
  905 UI(J)=UI(J)*AK/DEPTH
C
C         SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
C           (PARAMETERS)
C
      CALL PARAM
C
C         PRINT VALUES OF PARAMETERS
C
      PRINT 1020
 1020 FORMAT(1H0,17HPARAMETER VALUES-)
      DO 210 I=1,K0
  210 PRINT 1030,I,G(I)
 1030 FORMAT(1H ,I2,2X,E15.8)
      PRINT 1040
      PRINT 1050
 1050 FORMAT(1H0,17HDOWNSTREAM OXYGEN)
      PRINT 1060
 1060 FORMAT(1H ,2X,4HTIME,4X,9HPREDICTED,11X,8HOBSERVED)
C
C         SUBROUTINE COMPAR CALCULATES DOWNSTREAM OXYGEN CONCENTRATIONS FROM
C         UPSTREAM DATA AND COMPARES CALCULATED AND OBSERVED VALUES
C
      CALL COMPAR
C
C         INTEGRATE PRODUCTION OVER THE DARK INTERVALS AND DIVIDE BY THE
C         LENGTH OF THE INTERVALS TO CALCULATE MEAN RESPIRATION
C
      IF(KRAD.GT.0)   I1=TIM(I1)/DT+1.0
      IF(KRAD.GT.0)   I2=TIM(I2)/DT+1.0
      RMEAN=0.0
      QR=I1+KT-I2
      IF(QR.EQ.0) QR=1
      DO 211 I=1,I1
  211 RMEAN=RMEAN+CPROD(I)
```

```
      IU=KT
      DO 212 I=I2,IU
  212 RMEAN=RMEAN+QPROD(I)
      RMEAN=RMEAN-(QPROD(I1)+QPROD(I1)+QPROD(I2)+QPROD(IU))/2.0
      RMEAN=DAY*RMEAN/QR
C
C        CALCULATE NET AND GROSS PRODUCTION OF OXYGEN
C
      PNET=DAY*G(1)
      PGROS=PNET-RMEAN
      IF(KRAD.GE.1) GO TO 9
C
C        PRINT PRODUCTION, RESPIRATION AND RADIATION DATA
C
      PRINT 8,PNET,RMEAN,PGROS
    8 FORMAT(1H0,15HNET PRODUCTION=,F7.2,3X,12HRESPIRATION=,F7.2,3X,17HG
     +ROSS PRODUCTION=,F7.2,3X,27HNO RADIATION DATA AVAILABLE)
      GO TO 214
    9 PRINT 213,PNET,RMEAN,PGROS,RINT
  213 FORMAT(1H0,15HNET PRODUCTION=,F7.2,3X,12HRESPIRATION=,F7.2,3X,17HG
     +ROSS PRODUCTION=,F7.2,3X,16HTOTAL RADIATION=,F7.2)
  214 NIX=N
      IX=0
 6031 IX=IX+1
      NIX=NIX-50
      IF(NIX.GT.0) GO TO 6031
      XV=3.0
C
C        CALL INTERPOLATION ROUTINE TO ESTIMATE REGULARLY SPACED VALUES
C
      CALL INTERP(CAVG,N,TIM,KT,DT,MATO)
      CALL INTERP(CS,N,TIM,KT,DT,MATO)
      CALL INTERP(RAD,N,TIM,KT,DT,MATO)
C
C        CALL SUBROUTINES TO PLOT OXYGEN CONCENTRATION AND PRODUCTION
C        DATA OVER TIME AND PRODUCTION AGAINST RADIATION
C
      PRINT 6001,AL1,AL2,AL3,AL4,AL5
 6001 FORMAT(1H1,5A10,45HINTERPOLATED VALUES FOR OXYGEN AND SATURATION)
      CALL OXYPLOT(KT,CAVG,CS,XV,DT,VMIN,VMAX,IX)
      PRINT 5002,AL1,AL2,AL3,AL4,AL5
 5002 FORMAT(1H1,5A10)
      CALL PLOT(KT,QPROD,IX,XV,DT)
      IF(KRAD.NE.0)  CALL RADPLT(KT,QPROD,RAD,START,DT)
 7095 KSUM=0
 8099 KSUM=KSUM+1
      IF(KSUM.LE.2)  GO TO 8005
      NCHK=NCHK+1
      IF(NCHK.GE.NCMB) STOP
      GO TO 9000
C
C        PRINT A SUMMARY OF CALCULATIONS
```

```
C
 8005 PRINT 8066,AL1,AL2,AL3,AL4,AL5
 8066 FORMAT(1H1,27H*****      SUMMARY      *****,5X,5A10,///)
      PRINT 8070,AK,KO
 8070 FORMAT(1H ,12HRESPIRATION-,F5.2,5X,11HPARAMETERS-,I2)
      PRINT 8071,PNET
 8071 FORMAT(1H0,25X,14HNET PRODUCTION,3X,F7.2,3X,36HGRAMS OXYGEN PER CU
     +BIC METER PER DAY)
      PRINT 8072,RMEAN
 8072 FORMAT(1H ,25X,12HRESPIRATION-,5X,F7.2,3X,36HGRAMS OXYGEN PER CUBI
     +C METER PER DAY)
      PRINT 8073,PGROS
 8073 FORMAT(1H ,25X,17HGROSS PRODUCTION-,F7.2,3X,36HGRAMS OXYGEN PER CU
     +BIC 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,36H(RATIO OF GROSS PROD. TO TOT
     +AL RAD.))
      PRINT 8076,QPROD(1)
 8076 FORMAT(1H ,37X,F7.3,5X,17H(FROM REGRESSION))
      PRINT 8077,QPROD(2)
 8077 FORMAT(1H ,25X,10HINTERCEPT-,2X,F7.3)
      PRINT 8078,QPROD(3)
 8078 FORMAT(1H ,25X,12HCORRELATION-,F7.3,/////)
      GO TO 8099
      END
```

```
      SUBROUTINE SATURAT(CS,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,A6/14.589,0.392503,6.34716E-03,1.42111E-04,
     +1.07386E-05,1.65321E-07/
      DATA B1,B2,B3,B4,B5,B6 /13.2931,-.370225,1.01064E-02,-2.44128E-04,
     +3.76086E-06,-2.93824E-08/
      DATA C1,C2,C3,C4,C5,C6 /11.3993,-.284418,5.57208E-03,-1.76234E-05,
     +-3.00785E-06,4.75107E-08/
      S0=A1-A2*T+A3*T**2*A4*T**3-A5*T**4+A6*T**5
      S1=B1-B2*T+B3*T**2*B4*T**3-B5*T**4+B6*T**5
      S2=C1-C2*T+C3*T**2*C4*T**3-C5*T**4+C6*T**5
      IF(S-14.46)  10,10,15
   10 CS=S0+(S1-S0)*(S/14.46)
      RETURN
   15 CS=S1+(S2-S1)*(S-14.46)/34.3
      RETURN
      END
```

```
      SUBROUTINE PARAM
C
C        SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
C        (PARAMETERS).  THE COEFFICIENTS MUST BE CHOSEN TO MINIMIZE THE
C        CUMULATIVE ERROR, EXPRESSED AS THE SUM OF SQUARED ERRORS BETWEEN
C        OBSERVED AND CALCULATED DOWNSTREAM CONCENTRATIONS,  WHEN PARTIAL
C        DERIVATIVES OF THE ERROR WITH RESPECT TO EACH COEFFICIENT ARE
C        FORMED AND SET EQUAL TO ZERO, A SYSTEM OF LINEAR EQUATUONS IS
C        FOUND, WHICH MAY THEN BE SOLVED TO YIELD OPTIMUM VALUES FOR THE
C        PARAMETERS.
C
      COMMON/AL/AL1,AL2,AL3,AL4,AL5
      COMMON/A/AK,DT,K0,Z,N,W,KT,DEPTH
      COMMON/B/START,YSIN(50,100),UI(100),QPROD(100)
      COMMON/C/G(50),CAVG(100),CSURF(100),CS(100),TIM(100)
      DIMENSION B(50,50),C(50),CDIF(50)
      DIMENSION UL(50,50),GX(50)
      CHARACTER*10 AL1,AL2,AL3,AL4,AL5
      KS=0
C
C        CALCULATE LINEAR EQUATIONS
C
      B(1,1)=0.0
      DO 10 I=1,N
   10 B(1,1)=B(1,1)+TIM(I)/2.0
      DO 11 K=2,K0
      B(1,K)=0.0
      DO 11 J=1,N
   11 B(1,K)=B(1,K)+YSIN(K-1,J)/((K-1)*W)
      DO 12 K=2,K0
      B(K,1)=0.0
      DO 12 J=1,N
   12 B(K,1)=B(K,1)+(TIM(J)/2.0)*(YSIN(K-1,J)/((K-1)*W))
      DO 13 K=2,K0
      DO 13 L=2,K0
      B(K,L)=0.0
      DO 13 J=1,N
   13 B(K,L)=B(K,L)+(YSIN(K-1,J)/((K-1)*W))*(YSIN(L-1,J)/((L-1)*W))
      C(1)=0.0
      DO 14 J=1,N
   14 C(1)=C(1)-(CAVG(1)-CAVG(J)+UI(J))
      DO 15 K=2,K0
      C(K)=0.0
      DO 15 J=1,N
   15 C(K)=C(K)-(CAVG(1)-CAVG(J)+UI(J))*(YSIN(K-1,J)/((K-1)*W))
C
C        CALL SUBROUTINES TO SOLVE THE SYSTEM OF LINEAR EQUATIONS BY GAUSSIAN
C        ELIMINATION.  IF A SINGULAR MATRIX IS FOUND, STOP EXECUTION.
C
      CALL DECOMP(K0,B,UL,KS)
      IF(KS.GT.0) STOP
      CALL SOLVE(K0,UL,C,GX)
C
C        STORE OPTIMUM VALUES FOR THE PARAMETERS IN G.
C
      DO 400 J=1,K0
  400 G(J)=GX(J)
      G(1)=G(1)/2.0
      RETURN
      END
```

```
      SUBROUTINE COMPAR
C
C        SUBROUTINE COMPAR CALCULATES PREDICTED CONCENTRATIONS USING THE
C        EQUATION FOR DOWNSTREAM CONCENTRATION.  ERROR IN CALCULATION IS
C        EXPRESSED AS THE SUM OF SQUARED ERRORS BETWEEN OBSERVED AND
C        CALCULATED DOWNSTREAM CONCENTRATIONS.
C
      COMMON/AL/AL1,AL2,AL3,AL4,AL5
      COMMON/A/AK,DT,K0,Z,N,W,KT,DEPTH
      COMMON/B/START,YSIN(50,100),UI(100),QPROD(100)
      COMMON/C/G(50),CAVG(100),CSURF(100),CS(100),TIM(100)
      DIMENSION C(50),SUM(50),CPRED(100)
      CHARACTER*10 AL1,AL2,AL3,AL4,AL5
      DO 9 I=1,K0
    9 C(I)=G(I)
C
C        CALCULATE AND STORE PARTS OF THE EQUATION
C
      DO 10 J=1,N
      SUM(J)=0.0
      DO 10 M=2,K0
   10 SUM(J)=SUM(J)+(G(M)/((M-1)*W))*YSIN((M-1),J)
      DO 11 J=1,N
      CPRED(J)=CAVG(1)+UI(J)+(G(1)*TIM(J))+SUM(J)
C
C        PRINT TIME AND CALCULATED AND OBSERVED VALUES
C
   11 PRINT 1070,TIM(J),CPRED(J),CAVG(J)
 1070 FORMAT(1H ,F6.2,3X,E14.7,6X,E14.7)
C
C        CALCULATE AND PRINT SUM OF SQUARED ERRORS
C
      Z=0.0
      DO 13 J=1,N
   13 Z=Z+(CPRED(J)-CAVG(J))**2
      PRINT 1080,Z
 1080 FORMAT(1H0,22HSUM OF SQUARED ERRORS=,E14.7)
      PRINT 1090
 1090 FORMAT(1H0,4HTIME,5X,3HP-R)
      DO 110 J=1,KT
      T=J
      T=(T-1.0)*DT
      Y=C(1)
C
C        CALCULATE AND PRINT GROSS PRODUCTION
C
      DO 100 IS=2,K0
      Q=IS-1
  100 Y=Y+C(IS)*COS(Q*W*T)
      QPROD(J)=Y
      TIME=T+START
  108 IF(TIME.GT.24.0) GO TO 109
      PRINT 1100,TIME,Y
 1100 FORMAT(1H ,F6.2,3X,E15.8)
      GO TO 110
  109 TIME=TIME-24.0
      GO TO 108
  110 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE INTERP(MATI,N,TIM,KT,DT,MATO)
C
C         THIS SUBROUTINE CALCULATES REGULARLY SPACED VALUES OF A
C         QUANTITY FROM ERRATICALLY SPACED INPUT VALUES.
C
      REAL MATI(N),MATO(KT),TIM(N)
      DO 201 I=1,KT
  201 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)=MATI(1)
      IT=IT+1
      GO TO 1
    3 MATO(J)=MATI(N)
      NIT=NIT-1
    1 CONTINUE
      NN=N-1
      DO 9 I=1,NN
      IA=(TIM(I)/DT)+1.0
      IB=(TIM(I+1)/DT)+1.0
      IF(I.EQ.1)  IA=IT
      IF(I.EQ.N-1)  IB=NIT
      MATO(IA)=MATI(I)
      MATO(IB)=MATI(I+1)
      INT=IB-IA
      IF(INT.EQ.0)  GO TO 9
      DIFF=(MATO(IB)-MATO(IA))/INT
      IF(DIFF.NE.0.0)  GO TO 13
      DO 12 K=IA,IB
   12 MATO(K)=MATO(IA)
      GO TO 9
   13 IINT=INT-1
      DO 8 J=1,IINT
      MATO(J+IA)=J*DIFF+MATO(IA)
    8 CONTINUE
    9 CONTINUE
      DO 200 I=1,KT
  200 MATI(I)=MATO(I)
      RETURN
      END
```

```
      SUBROUTINE OXYPLOT(MPT,X1,X2,XVAL,CPLOT,VMIN,VMAX,IX)
C
C        THIS SUBROUTINE PLOTS OXYGEN CONCENTRATION AGAINST TIME
C
      COMMON/A/AK,DT,K0,Z,N,W,KT,DEPTH
      COMMON/B/START,YSIN(50,100),UI(100),QPROD(100)
```

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

```
      SUBROUTINE PLOT(MPT,VAL,IX,XVAL,CPLOT)
C
C        THIS SUBROUTINE PLOTS OXYGEN PRODUCTION AGAINST TIME.
C
      COMMON/A/AK,DT,K0,Z,N,W,KT,DEPTH
      COMMON/B/START,YSIN(50,100),UI(100),QPROD(100)
```

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

Table B1

Definition of FORTRAN Variables

FORTRAN Identifier	Definition
CAVG	Average oxygen concentration over depth
CSURF	Surface oxygen concentration
DEPTH	Depth
RAD	Radiation
SAL	Salinity
TEMP	Surface temperature
TIM	Time at which data are collected

Table B2

Cards for Input to Standing Water, Depth Average Program

Card Number	Variables	Format
1	NUMB	I2
2	AL1,AL2,AL3,AL4,AL5	5A10
3	KRAD,THRS	I2,F10
4	SAL,DT,PRES,N,KO	I6,2F10,2I5
5	AK,START	2F10
6	DEPTH	F10
7 through N+7	TIM(I),CAVG(I),CSURF(I), TEMP(I)	Free field
N+8	F1,F2	2F10

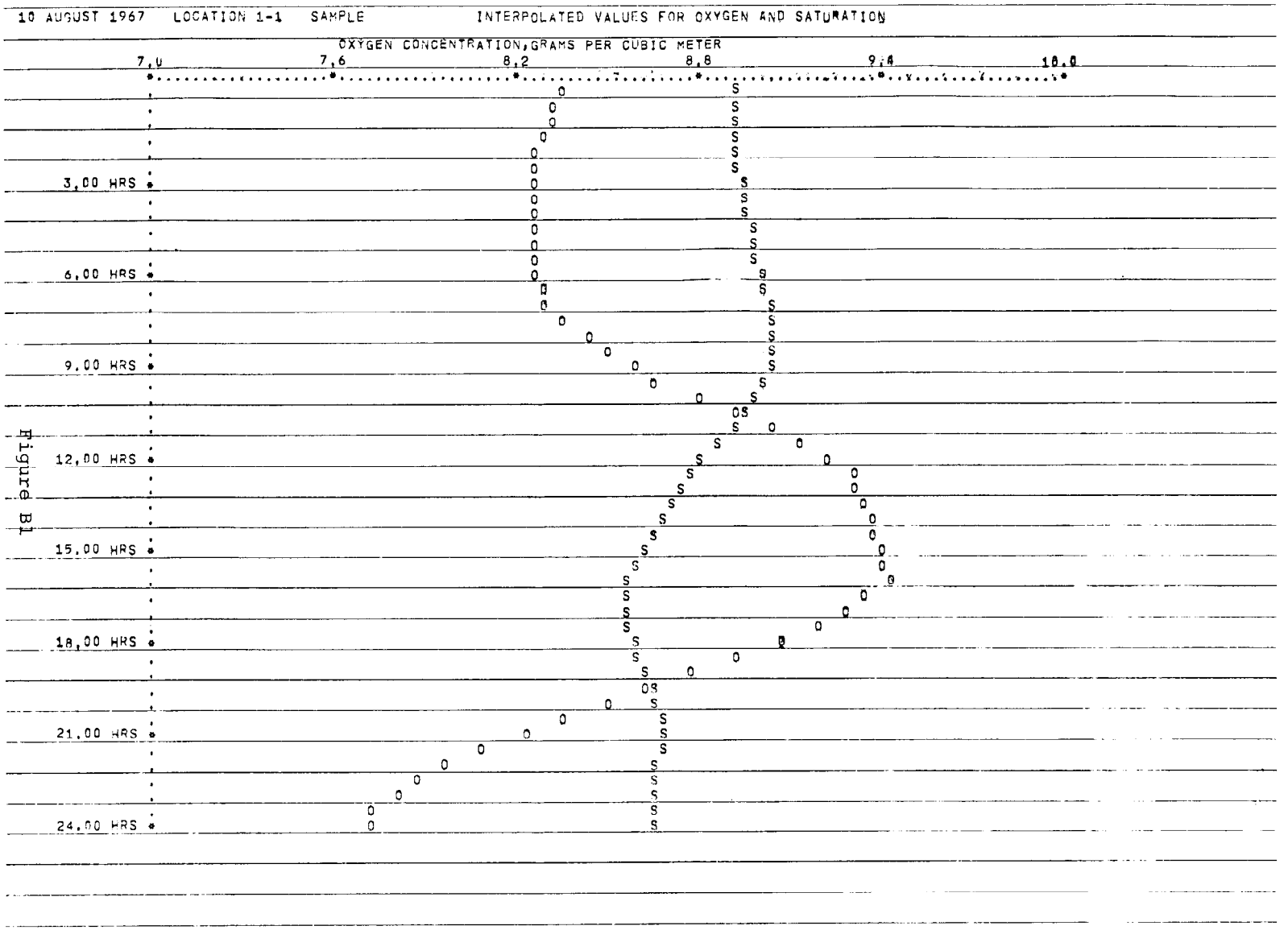

Figure B1

Figure B1. Example of line printer plots for standing water depth averaged program (sheet 1 of 3)

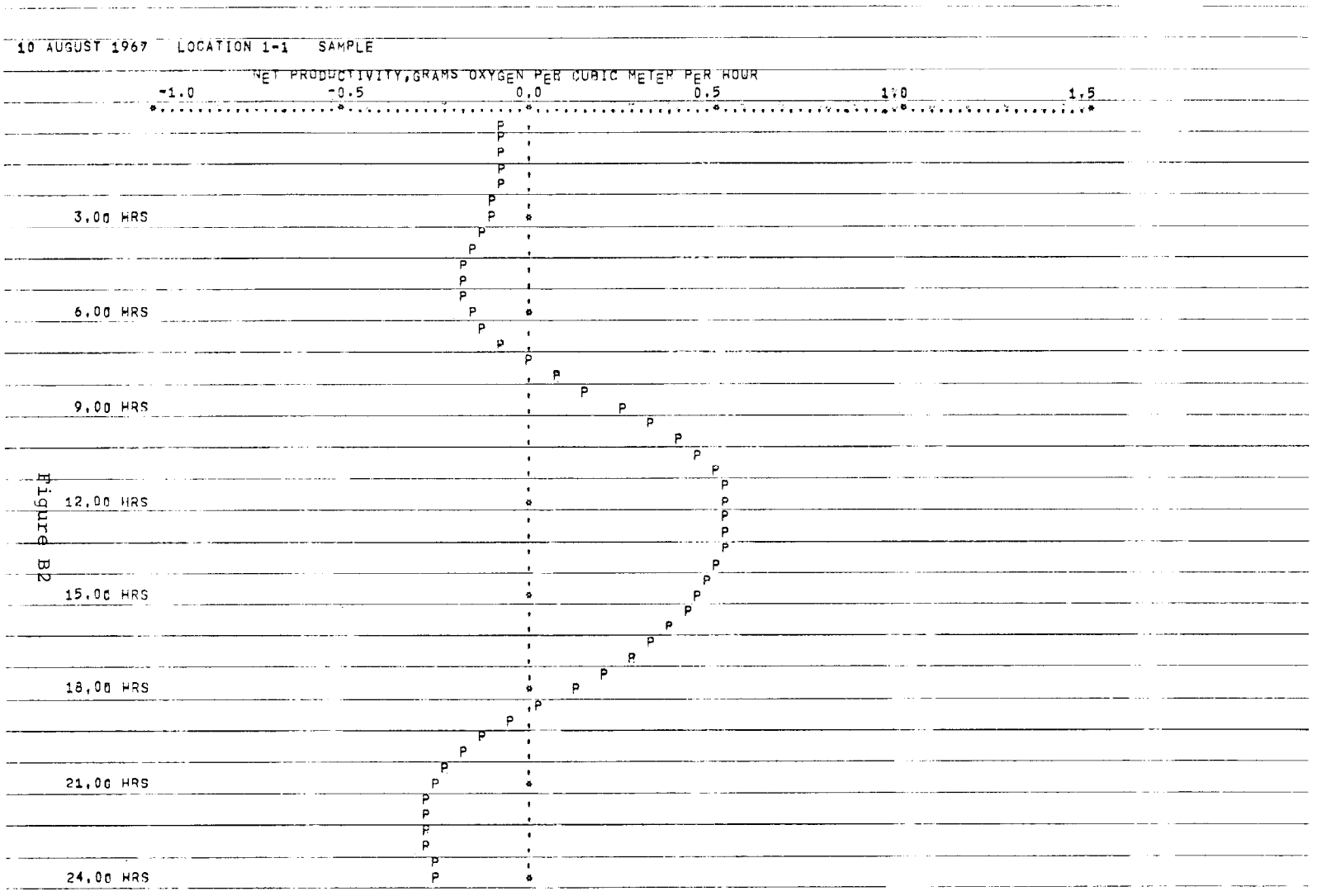

Figure B2

Figure B1. (sheet 2 of 3)

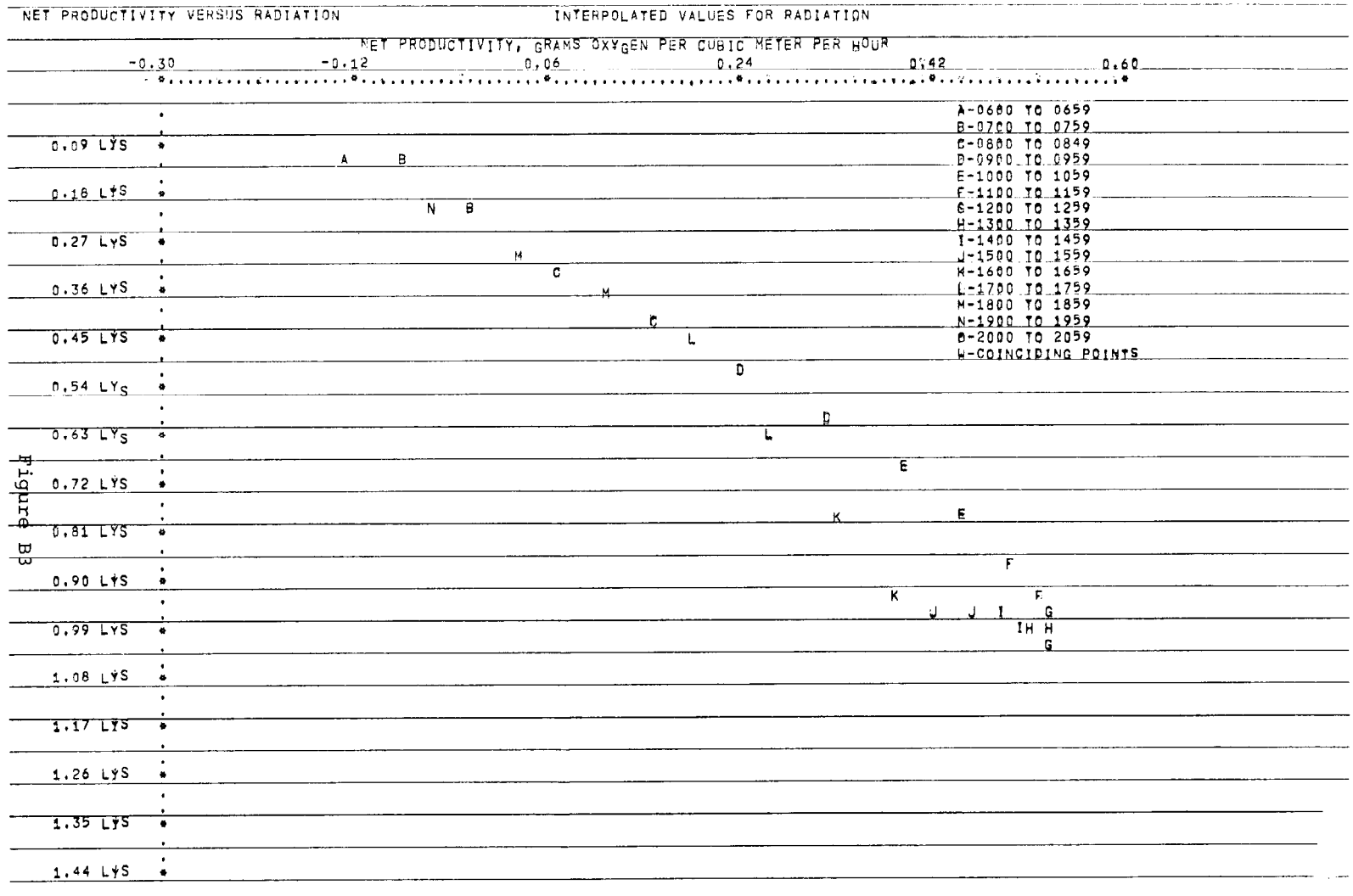

Figure B3

Figure B1. (sheet 3 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 M. 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 B. MOLER (PRENTICE-HALL, 1967).

METHOD

OXYGEN MEASUEMENTS ARE TAKEN IN A LAKE AT POINTS SEPARATED BY A CONSTANT VERTICAL DISTANCE. THE RATE OF CHANGE OF OXYGEN CONCENTRATION AT A DEPTH I MAY BE REPRESENTED BY THE EQUATION

```
DC(I)/DT=(DV(I+1/2)*C(I+1)-(DV(I+1/2)*DV(I-1/2))*C(I)
        +DV(I-1/2)*C(I-1))/Z**2 + (P-R)(I)
```

WHERE C(I) = CONCENTRATION AT DEPTH I
DV(I) = DISPERSION COEFFICIENT AT DEPTH I
Z = DISTANCE BETWEEN DEPTHS
(P-R)(I) = NET PRODUCTIVITY AT DEPTH I

THE EQUATION FOR THE SURFACE LAYER MAY BE WRITTEN

```
DC(1)/DT = 2*DV(1+1/2)*C(2)/Z**2 - (2*K*DV(1+1/2)
    /(DV(1)*Z))*CS - (2*DV(1+1/2)/Z**2)*(1-(K*Z)
    /DV(1))*C(1) + (P-R)(1)
```

K = REAERATION COEFFICIENT
CS = SATURATION CONCENTRATION

NET PRODUCTIVITY AT ANY DEPTH MAY BE REPRESENTED BY A FOURIER SERIES

```
P-R = A0/2 + SUM FROM N=1 TO K0 OF (AN*COS(N*W*T))
```

WHERE AN = COEFFICIENTS
W = 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.

```
      CHARACTER*10 AL1,AL2,AL3,AL4,AL5
      COMMON/S/START,DT
      COMMON/GO/N,KO,IX,Z,RK,W,S
      COMMON/BV/DV1,DV(50)
      COMMON/AR/CS(100),G(20),DO(100,50),PROD(100,50)
      COMMON/AL/AL1,AL2,AL3,AL4,AL5,AK
      COMMON/T/THRS
      DIMENSION RAD(100),M(50),DUMMY(100)
      DATA A1,A2,A3,A4,A5,A6/14.589,0.392503,6.34716E-03,1.42111E-04,
     +1.07386E-05,1.65321E-07/
C
C        READ IN NUMBER OF DAYS TO RUN
C
      READ 19,NUMB
   19 FORMAT(I2)
      NCHK=0
C
C        READ IN ALPHANUMERIC CHARACTERS FOR LOCATION AND DATE
C
 9000 READ 5000,AL1,AL2,AL3,AL4,AL5
 5000 FORMAT(5A10)
C
C        READ IN DATA MODE INFORMATION
C
C              KRAD=0  NO RADIATION DATA AVAILABLE
C                  =1  RADIATION MEASURED
C
C              THRS=THRESHOLD VALUE FOR RADIATION
C
      READ 20,KRAD,THRS
   20 FORMAT(I2,F10.4)
C
C        READ IN  Z=THICKNESS OF LAYERS
C                DT=DATA INTERVAL
C              PRES=ATMOSPHERIC PRESSURE
C                 N=NUMBER OF DATA POINTS
C                KO=NUMBER OF PARAMETERS
C                IX=NUMBER OF DEPTHS
C
      READ 5,Z,DT,PRES,N,KO,IX
    5 FORMAT(3F10.0,3I5)
      IXS=IX
C
C        READ IN    RK=REAERATION COEFFICIENT
C                START=STARTING TIME
C
      READ 10,RK,START
   10 FORMAT(2F10.0)
C
C        INITIALIZE ARRAYS
```

```
C
      DO 220 K=1,IXS
      CS(K)=0.0
      DV(K)=0.0
      DO 220 J=1,N
  220 DO(J,K)=0.0
      DO 221 J=1,N
  221 RAD(J)=0.0
C
C        READ IN DISPERSION COEFFICIENT FOR EACH DEPTH (METERS SQUARED PER HOUR)
C
      DO 600 I=1,IX
  600 READ 21,DV(I)
   21 FORMAT(F10.0)
      DV1=DV(1)
      IX=IX-1
      DO 601 I=1,IX
  601 DV(I)=(DV(I)+DV(I+1))/2.0
C
C        READ IN TEMPERATURE (DEGREES CENTIGRADE)
C                RADIATION IF MEASURED (LANGLEYS)
C
 6100 FORMAT(V)
      DO 602 I=1,N
      IF(KRAD.EQ.0)   READ 6100,CS(I)
  602 IF(KRAD.GT.0)   READ 6100,CS(I),RAD(I)
C
C        READ IN OXYGEN CONCENTRATIONS (GRAMS PER CUBIC METER)
C
      DO 620 I=1,N
  620 READ 6100,(DO(I,J),J=1,IXS)
C
C        READ IN NUMBER OF DEPTHS TO BE PLOTTED
C
      READ 630,MR
  630 FORMAT(I3)
      IF(MR.EQ.0)   GO TO 4
C
C        READ IN DEPTHS TO BE PLOTTED
C
      DO 631 I=1,MR
  631 READ 630,M(I)
C
C        IF NO RADIATION DATA IS AVAILABLE, READ IN TIME OF SUNRISE AND SUNSET
C
    4 IF(KRAD.EQ.0)   READ 1,F1,F2
    1 FORMAT(2F10.0)
      I1=(F1+START)/DT+1.0
      I2=(F2+START)/DT+1.0
C
      DAY=FLOAT(N-1)*DT
      W=6.28318/(2.0*DAY)
```

```
C
C         CONVERT TEMPERATURE TO SATURATION CONCENTRATION OF OXYGEN
C         CORRECT SATURATION FOR ATMOSPHERIC PRESSURE
C
      CORR=PRES/1013.25
  619 DO 70 I=1,N
      CS(I)=A1-A2*CS(I)+A3*CS(I)**2+A4*CS(I)**3- A5*CS(I)**4+A6*CS(I)**5
   70 CS(I)=CS(I)*CORR
C
C         CALCULATE THE INTEGRAL OF RADIATION OVER THE INTERVAL FROM SUNRISE
C           TO SUNSET, USING THE TRAPEZOIDAL RULE
C
      RINT=0.0
      IF(KRAD.EQ.0) GO TO 750
      IF(RAD(1).GT.THRS)   GO TO 750
      I1=10000
      DO 740 I=1,N
      IF(RAD(I).LE.THRS)   GO TO 730
      IF(I1.GT.I) I1=I-1
      RINT=RINT+(RAD(I-1)+RAD(I))*DT
      I2=I+1
      GO TO 740
  730 IF(I.EQ.1) GO TO 740
      IF(RAD(I-1).LE.THRS)   GO TO 740
      RINT=(RAD(I-1)+RAD(I))*DT+RINT
  740 CONTINUE
      IF(I1.EQ.0) I1=1
      RINT=RINT*60.0/2.0
      IF(RINT.EQ.0) KRAD=0
  750 CONTINUE
      DO 555 II=1,IX
C
C         PRINT HEADINGS
C
      PRINT 6000
 6000 FORMAT(1H1,50H**************************************************)
      PRINT 1040
 1040 FORMAT(1H0,50H**************************************************)
      PRINT 1070,II
 1070 FORMAT(1H0,22HNET PRODUCTIVITY-DEPTH,I3,//)
      PRINT 1040
      PRINT 5001,AL1,AL2,AL3,AL4,AL5
 5001 FORMAT(1H ,5A10)
      PRINT 1040
C
      AK=2.*DV(1)/Z**2
      AK=AK*(1.-RK*Z/DV1)
      IF(II.GT.1)   AK=(DV(II)+DV(II-1))/Z**2
      S=EXP(-AK*DT)
C
C         SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
C           (PARAMETERS)
```

```
      JK=II
      CALL PARAM(JK)
C
C        PRINT VALUES OF PARAMETERS
C
      PRINT 1020
 1020 FORMAT(1H0,17HPARAMETER VALUES-)
      DO 210 I=1,K0
  210 PRINT 1030,I,G(I)
 1030 FORMAT(1H ,I2,2X,E15.8)
      PRINT 1040
      PRINT 1050
 1050 FORMAT(1H0,20HOXYGEN CONCENTRATION)
      PRINT 1060
 1060 FORMAT(1H ,2X,4HTIME,4X,9HPREDICTED,11X,8HOBSERVED)
      IF(II.EQ.1)   PRINT 1061
 1061 FORMAT(1H+,50X,10HSATURATION)
C
C        SUBROUTINE COMPAR CALCULATES DOWNSTREAM OXYGEN CONCENTRATIONS FROM
C        UPSTREAM DATA AND COMPARES CALCULATED AND OBSERVED VALUES
C
      CALL COMPAR(JK)
C
C        INTEGRATE PRODUCTION OVER THE DARK INTERVALS AND DIVIDE BY THE
C        LENGTH OF THE INTERVALS TO CALCULATE MEAN RESPIRATION
C
      RMEAN=0.0
      IF(RAD(1).GT.THRS)   GO TO 215
      QR=I1+N-I2
      IF(QR.EQ.0) QR=1
      DO 211 I=1,I1
  211 RMEAN=RMEAN+PROD(I,II)
      DO 212 I=I2,N
  212 RMEAN=RMEAN+PROD(I,II)
      RMEAN=RMEAN-(PROD(1,II)+PROD(I1,II)+PROD(I2,II)+PROD(N,II))/2.0
      RMEAN=DAY*RMEAN/QR
C
C        CALCULATE NET AND GROSS PRODUCTION OF OXYGEN
C
  215 PNET=DAY*G(1)
      PGROS=PNET-RMEAN
      IF(KRAD.GE.1) GO TO 9
C
C        PRINT PRODUCTION, RESPIRATION AND RADIATION DATA
C
      PRINT 8,PNET,RMEAN,PGROS
    8 FORMAT(1H0,15HNET PRODUCTION=,F7.2,3X,12HRESPIRATION=,F7.2,3X,17HG
     +ROSS PRODUCTION=,F7.2,3X,27HNO RADIATION DATA AVAILABLE)
      GO TO 214
    9 PRINT 213,PNET,RMEAN,PGROS,RINT
  213 FORMAT(1H0,15HNET PRODUCTION=,F7.2,3X,12HRESPIRATION=,F7.2,3X,17HG
```

```
     +ROSS PRODUCTION=,F7.2,3X,16HTOTAL RADIATION=,F7.2)
C
C         DETERMINE WHETHER CURRENT DEPTH IS TO BE PRINTED
C
  214 NIX=(N/50)+1
      INDEX=0
      DO 400 I=1,MR
  400  IF(II.EQ.M(I))   INDEX=1
      IF(INDEX.EQ.0)   GO TO 8005
C
C
C         CALCULATE MAXIMUM AND MINIMUM VALUES FOR CONCENTRATION
C
      VMIN=1000.0
      VMAX=-1000.0
      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)
C
C         CALL SUBROUTINE TO PLOT OXYGEN CONCENTRATION
C
      PRINT 6001,AL1,AL2,AL3,AL4,AL5,II
 6001 FORMAT(1H1,5A10,30HOXYGEN AND SATURATION AT DEPTH,I3)
      DO 590 K=1,N
  590 DUMMY(K)=DO(K,II)
      CALL OXYPLOT(N,DUMMY,CS,3.0,DT,VMIN,VMAX,NIX,JK)
C
C         CALL SUBROUTINE TO PLOT OXYGEN PRODUCTION
C
      PRINT 6002,AL1,AL2,AL3,AL4,AL5,II
 6002 FORMAT(1H1,5A10,23HNET PRODUCTION AT DEPTH,I3)
      DO 591 K=1,N
  591 DUMMY(K)=PROD(K,II)
      CALL PLOT(N,DUMMY,NIX,3.0,DT)
C
C         CALL SUBROUTINE TO PLOT RADIATION AGAINST PRODUCTION
C
      IF(KRAD.NE.0)   CALL RADPLT(N,DUMMY,RAD,START,DT)
C
C         PRINT A SUMMARY OF CALCULATIONS
C
 8005 DO 560 I=1,2
      PRINT 8066,AL1,AL2,AL3,AL4,AL5
 8066 FORMAT(1H1,27H*****      SUMMARY      *****,5X,5A10,///)
      PRINT 8067,II
 8067 FORMAT(1H0,5HDEPTH,I3)
      PRINT 8071,PNET
 8071 FORMAT(1H0,25X,14HNET PRODUCTION,3X,F7.2,3X,36HGRAMS OXYGEN PER CU
     +BIC METER PER DAY)
      PRINT 8072,RMEAN
 8072 FORMAT(1H ,25X,12HRESPIRATION-,5X,F7.2,3X,36HGRAMS OXYGEN PER CUBI
     +C METER PER DAY)
```

```
      PRINT 8073,PGROS
 8073 FORMAT(1H ,25X,17HGROSS PRODUCTION-,F7.2,3X,36HGRAMS OXYGEN PER CU
     +BIC METER PER DAY)
      IF(KRAD.EQ.0)   GO TO 560
      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,36H(RATIO OF GROSS PROD. TO TOT
     +AL RAD.))
      IF(INDEX.LT.1)   GO TO 560
      PRINT 8076,DUMMY(1)
 8076 FORMAT(1H ,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
  555 CONTINUE
      NCHK=NCHK+1
      IF(NCHK.GE.NUMB)   STOP
      GO TO 9000
      END
```

```
      FUNCTION CSI(I,J)
C
C        THIS FUNCTION STORES PART OF THE EQUATION FOR PREDICTED OXYGEN
C        CONCENTRATION
C
      COMMON/S/START,DT
      COMMON/CO/N,KO,IX,Z,RK,W,S
      COMMON/DV/DV1,DV(50)
      COMMON/AR/CS(100),G(20),DO(100,50),PROD(100,50)
      IF(I.EQ.1)   GO TO 100
C
C        MIDDLE LAYERS
C
      AK=(DV(I)+DV(I-1))/Z**2
      AL=DV(I)/Z**2
      AM=DV(I-1)/Z**2
      AV=(DO(J+1,I+1)+DO(J,I+1))/2.0
      AV=AV*AL
      AVG=(DO(J+1,I-1)+DO(J,I-1))/2.0
      AVG=AVG*AM
      CSS=(AV+AVG)/AK
      CSI=CSS*(1.0-S)
      RETURN
C
C        TOP LAYER
C
  100 AK=2.*DV(I)/Z**2
      AK=AK-(2.*DV(I)*RK/(DV1*Z))
      AL=2.0*DV(I)/Z**2
      AM=2.*RK*DV(I)/(DV1*Z)
      AV=(DO(J+1,I+1)+DO(J,I+1))/2.0
      AV=AV*AL
      AVG=(CS(J+1)+CS(J))/2.0
      AVG=AVG*AM
      CSS=(AV-AVG)/AK
      CSI=CSS*(1.0-S)
      RETURN
      END
```

```
      SUBROUTINE PARAM()
C
C        SUBROUTINE PARAM CALCULATES THE VALUES OF THE FOURIER COEFFICIENTS
C        (PARAMETERS).  THE COEFFICIENTS MUST BE CHOSEN TO MINIMIZE THE
C        CUMULATIVE ERROR, EXPPESSED AS THE SUM OF SQUARED ERRORS BETWEEN
C        OBSERVED AND CALCULATED DOWNSTREAM CONCENTRATIONS,  WHEN PARTIAL
C        DERIVATIVES OF THE ERROR WITH RESPECT TO EACH COEFFICIENT ARE
C        FORMED AND SET EQUAL TO ZERO, A SYSTEM OF LINEAR EQUATIONS IS
C        FOUND, WHICH MAY THEN BE SOLVED TO YIELD OPTIMUM VALUES FOR THE
C        PARAMETERS.
C
      COMMON/S/START,DT
      COMMON/CO/N,KO,IX,Z,RK,W,S
      COMMON/AR/CS(100),G(20),DO(100,50),PROD(100,50)
      COMMON/AL/AL1,AL2,AL3,AL4,AL5,AK
      CHARACTER*10 AL1,AL2,AL3,AL4,AL5
      DIMENSION GAM(100,20),B(20,20),C(20),A(100),UL(20,20)
      ZCOS(N,J)=COS((N-1)*W*(START+(J-1)*DT))
      ZSIN(N,J)=SIN((N-1)*W*(START+(J-1)*DT))
      KS=0
      N=N-1
C
C        BREAK DOWN THE EQUATION FOR DOWNSTREAM CONCENTRATION INTO ITS
C        COMPONENT PARTS A, B1 AND GAM
C
      DO 10 J=1,N
      L=J
   10 A(J)=CSI(1,L)+S*DO(L,1)
      DO 20 L=1,N
      GAM(L,1)=0.0
      DO 20 IS=2,KO
      V=IS-1
      LO=L+1
      W1=1.0/(AK**2+(V*W)**2)
      W2=AK*ZCOS(IS,LO)+V*W*ZSIN(IS,LO)-S*(AK*ZCOS(IS,L)+V*W*
     1ZSIN(IS,L))
   20 GAM(L,IS)=W1*W2
C
C        SET UP MATRICES B AND C TO CONTAIN THE LINEAR SYSTEM FOUND FROM
C        MINIMIZING THE ERROR, SUCH THAT B*A=C (WHERE MATRIX A CONTAINS
C        THE PARAMETERS).
C
  320 DO 30 K=2,KO
      DO 30 J=2,KO
      B(K,J)=0.
      DO 30 L=1,N
   30 B(K,J)=B(K,J)+GAM(L,J)*GAM(L,K)
      B1=(1.0-S)/(2.0*AK)
      B(1,1)=B1*N
      DO 40 K=2,KO
      C(K)=0.
      B(1,K)=0.
```

```
      DO 35 L=1,N
      B(1,K)=B(1,K)+GAM(L,K)
   35 C(K)=C(K)+GAM(L,K)*(DO(L+1,I)-A(L))
   40 B(K,1)=B1*B(1,K)
      C(1)=0.0
      DO 80 L=1,N
   80 C(1)=C(1)+DO(L+1,I)-A(L)
C
C        CALL SUBROUTINES TO SOLVE THE SYSTEM OF LINEAR EQUATIONS BY GAUSSIAN
C        ELIMINATION.  IF A SINGULAR MATRIX IS FOUND, STOP EXECUTION.
C
   81 CALL DECOMP(KO,B,UL,KS)
      IF(KS.GT.0) STOP
      CALL SOLVE(KO,UL,C,G)
      G(1)=G(1)/2.0
      N=N+1
      RETURN
      END
```

```
      SUBROUTINE COMPAR(I)
C
C         SUBROUTINE COMPAR CALCULATES PREDICTED CONCENTRATIONS USING THE
C         EQUATION FOR DOWNSTREAM CONCENTRATION.  ERROR IN CALCULATION IS
C         EXPRESSED AS THE SUM OF SQUARED ERRORS BETWEEN OBSERVED AND
C         CALCULATED DOWNSTREAM CONCENTRATIONS.
C
      COMMON/S/START,DT
      COMMON/CO/N,KO,IX,Z,RK,W,S
      COMMON/AP/CS(100),G(20),DO(100,50),PROD(100,50)
      COMMON/AL/AL1,AL2,AL3,AL4,AL5,AK
      CHARACTER*10 AL1,AL2,AL3,AL4,AL5
C
C         CALCULATE AND STORE PARTS OF THE EQUATION
C
      ZCOS(N,J)=COS((N-1)*W*(START+(J-1)*DT))
      ZSIN(N,J)=SIN((N-1)*W*(START+(J-1)*DT))
      AZ=0.0
      N=N-1
C
      DO 90 L=1,N
      LL=L
      R1=S*DO(LL,I)*CSI(I,LL)
      R1=R1+(G(1)/AK)*(1.0-S)
      R2=0
      DO 50 NM=2,KO
      W1=AK**2+((NM-1)*W)**2
      W1=G(NM)/W1
      W2=AK*ZCOS(NM,L+1)+(NM-1)*W*ZSIN(NM,L+1)
      W2=W2-S*(AK*ZCOS(NM,L)+(NM-1)*W*ZSIN(NM,L))
   50 R2=R2+W1*W2
C
C         CALCULATE CONCENTRATION AND TIME
C
   60 R=R1+R2
      TIME=START+L*DT
C
C         PRINT TIME AND CALCULATED AND OBSERVED VALUES
C
      PRINT 1070,TIME,R,DO(L+1,I)
 1070 FORMAT(1H ,F6.2,3X,F14.7,6X,F14.7)
      IF(I.EQ.1)   PRINT 1071,CS(L)
 1071 FORMAT(1H+,49X,E14.7)
C
C         CALCULATE AND PRINT SUM OF SQUARED ERRORS
C
   90 AZ=AZ+(R-DO(L+1,I))**2
   75 PRINT 1080,AZ
 1080 FORMAT(1H0,22HSUM OF SQUARED ERRORS=,F14.7)
C
C         CALCULATE AND PRINT GROSS PRODUCTION
C
```

```
      PRINT 1090
 1090 FORMAT(1H0,4HTIME,5X,3HP-R)
      NN=N+1
      DO 110 J=1,NN
      Y=G(I)
      DO 100 IS=2,KO
  100 Y=Y+G(IS)*ZCOS(IS,J)
      PROD(J,I)=Y
      TIME=START+(J-1)*DT
      PRINT 1100,TIME,Y
 1100 FORMAT(1H ,F6.2,3X,E15.8)
  110 CONTINUE
      N=N+1
      RETURN
      END
```

Table C1

Definitions of FORTRAN Variables

FORTRAN Identifier	Definition
DO(I,J)	Dissolved oxygen at time I and depth J
DV	Dispersion coefficient
IX	Number of depths at which data are collected
MR	Number of depths for which a line printer graph is desired
RK	Reaeration coefficient
Z	Depth interval

Table C2

Cards for Input to Standing Water, Depth Distribution Program

Card Number	Variables	Format
1	NUMB	I2
2	AL1,AL2,AL3,AL4,AL5	5A10
3	KRAD,THRS	I2,F10
4	Z,DT,PRES,N,KO,IX	3F10,3I5
5	RK,START	2F10
6 through IX+6	DV(I)	F10
IX+7 through N+IX+7	CS(I),RAD(I)	Free field
N+IX+7 through 2N+IX+7	DO(I,J),J=1 through IX	Free field
2N+IX+8	MR	I3
2N+IX+9	F1,F2	2F10

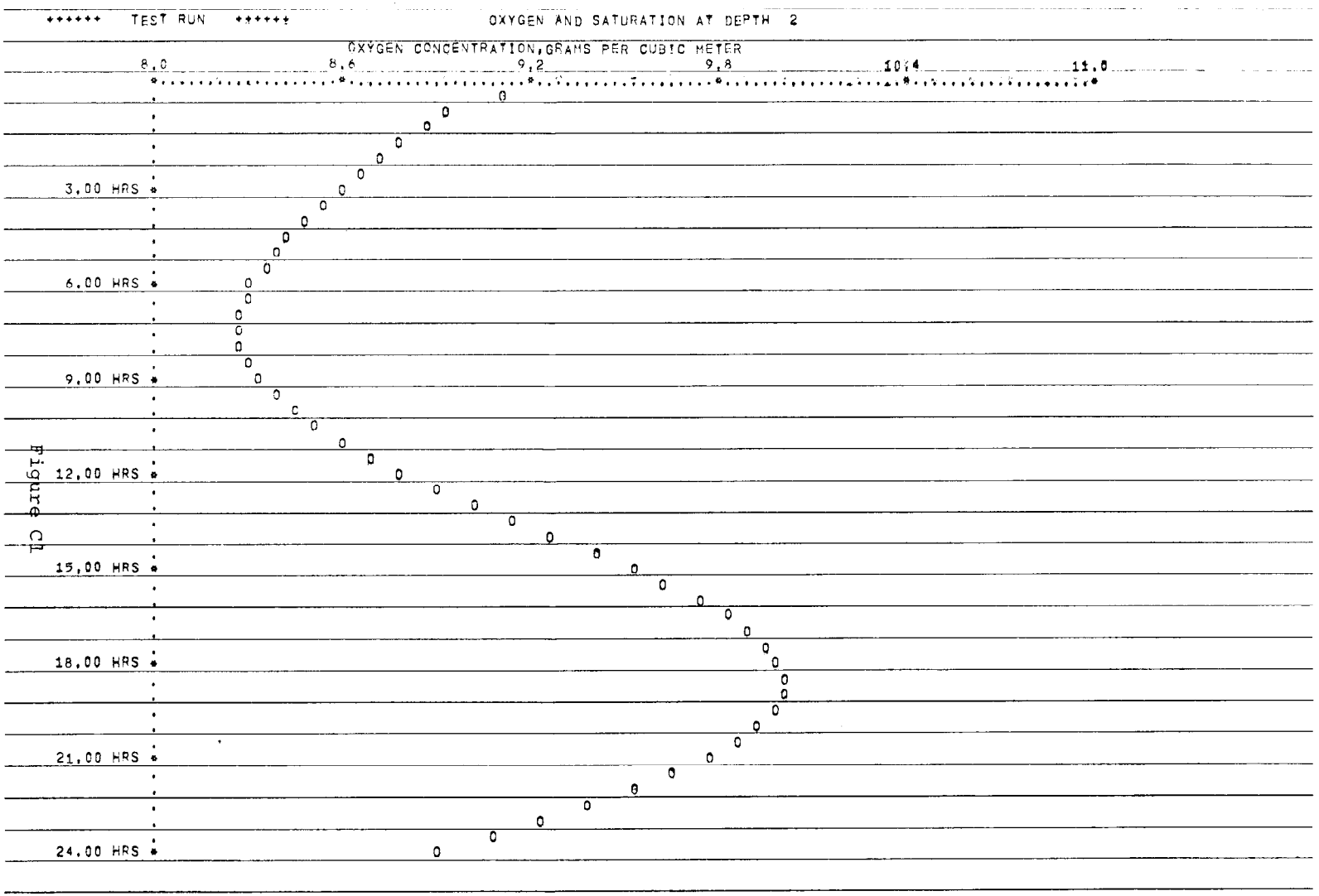

Figure C1

Figure C1. Sample output, standing water depth distribution program (sheet 1 of 3)

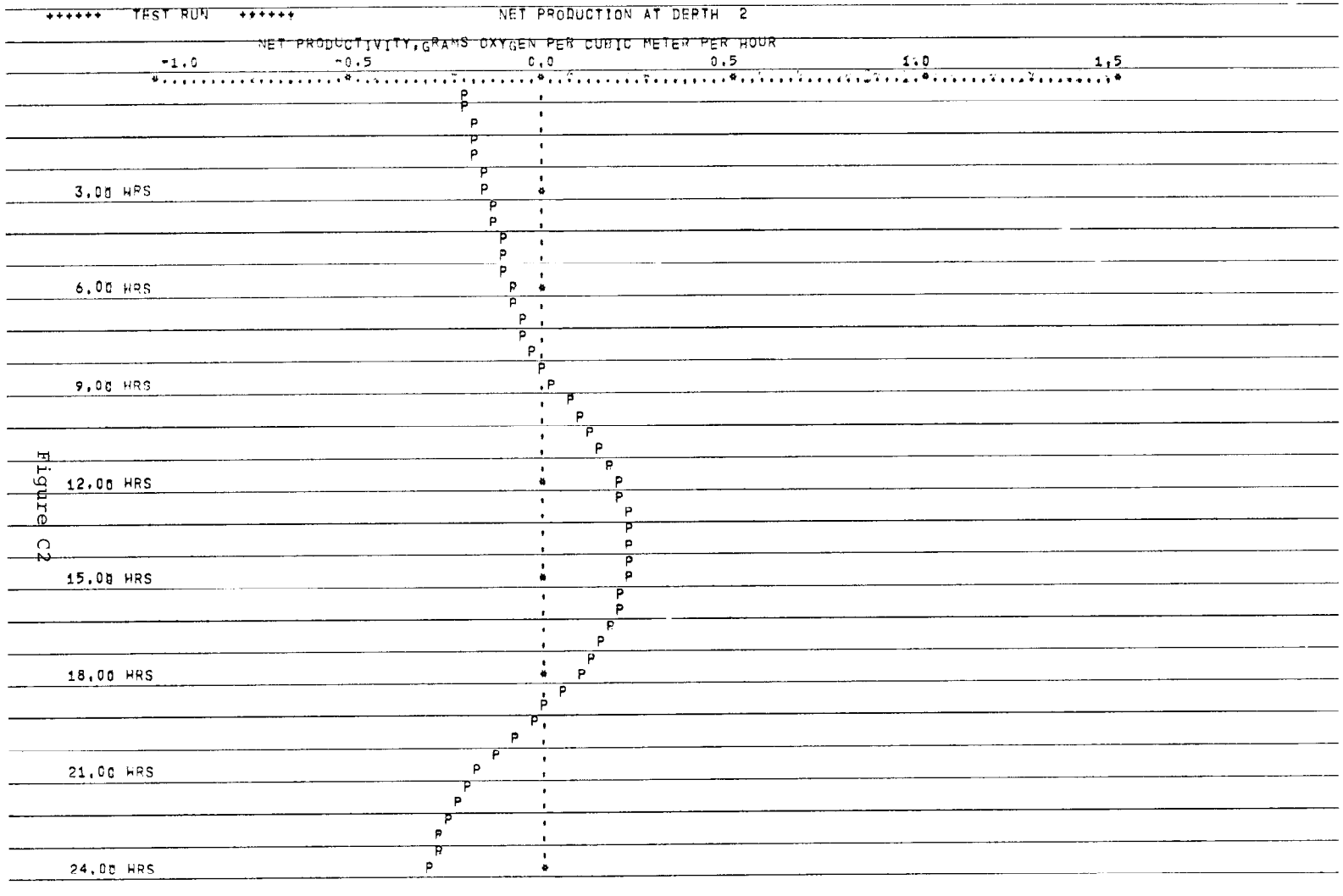

Figure C2

Figure C1. (sheet 2 of 3)

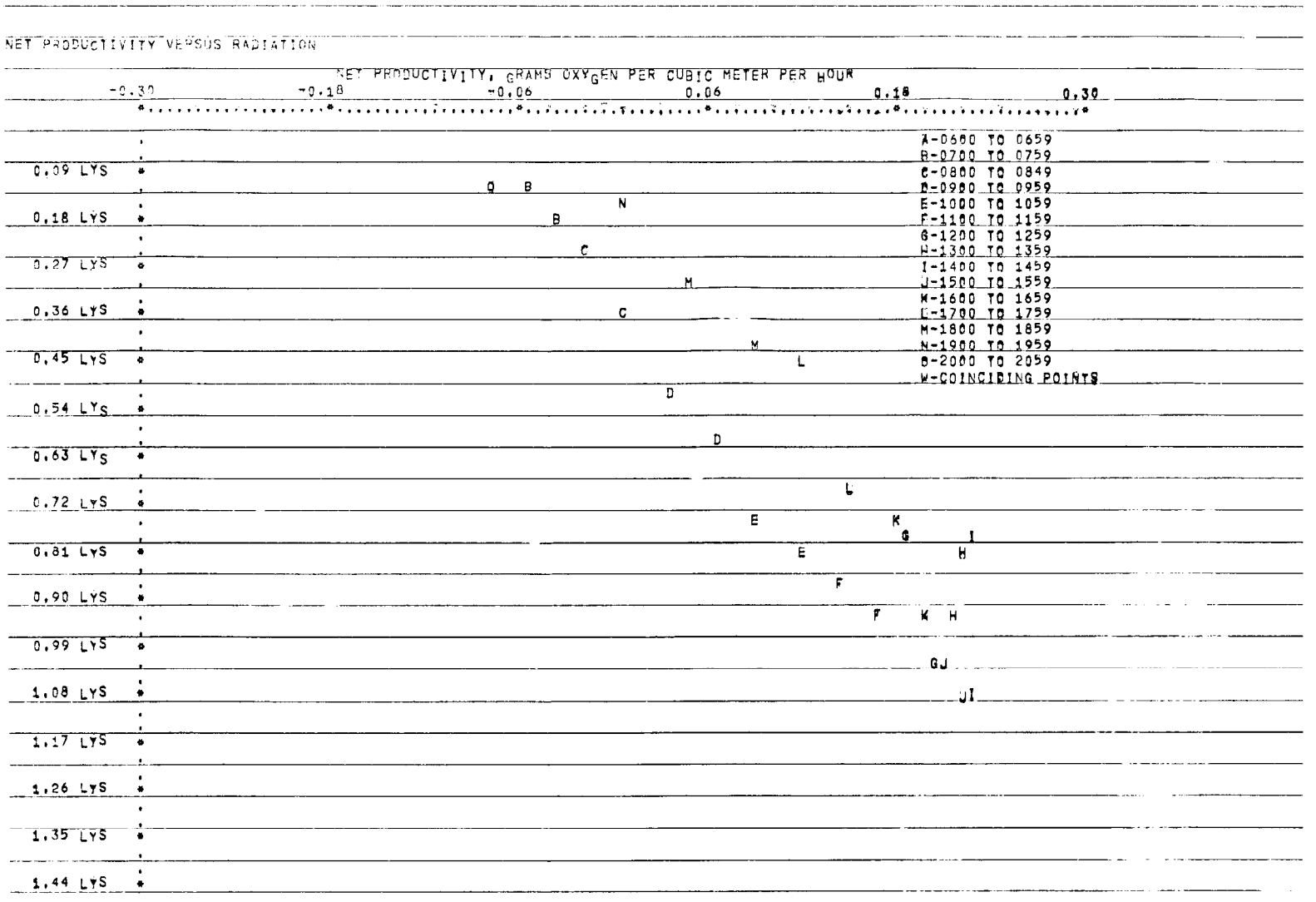

Figure C1. (sheet 3 of 3)

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	$2\pi/48$

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. DACW-39-74-C-0030, (DMRP Work Unit 1D04)

Includes bibliography.

1. Aquatic environment. 2. Biochemical oxygen demand. 3. Computer programs. 4. Dredged material. 5. Metabolism. 6. Oxygen. I. Hornberger, George M. II. Kelly, Mahlon G., joint author. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Contract report D-75-3)

TA7.W34c no.D-75-3