SEA GRANT COLLEGE TECHNICAL REPORT

WIS-SG-75-228

A COMPUTER ANALYSIS OF THE WATER QUALITY IN THE LOWER FOX RIVER AND LOWER GREEN BAY, WISCONSIN

ROBERT W. LANZ

THE UNIVERSITY OF WISCONSIN

The author wishes to express gratitude to the University of Wisconsin Sea Grant Program, since this project was funded by the National Oceanic and Atmospheric Administration's Office of Sea Grant, Department of Commerce, through an institutional grant to the University of Wisconsin. The author wishes to further acknowledge the efforts of Steven Root, who contributed greatly to the development of this work.

SEA GRANT COMMUNICATIONS OFFICE
1800 University Avenue
Madison, Wisconsin 53706

608/263-3259

WIS-SG-75-228

A COMPUTER ANALYSIS OF THE WATER QUALITY IN THE LOWER FOX RIVER AND LOWER GREEN BAY, WISCONSIN

by

R. W. Lanz

Associate Professor of Environmental Control

University of Wisconsin-Green Bay

UNIVERSITY OF WISCONSIN SEA GRANT COLLEGE PROGRAM

Technical Report #228

August 1975

Contents

	Abstract	1
I.	Introduction	3
II.	Computer Stations, Flow Times	3
III.	Biological Oxidation - Reduction Factors	4
IV.	Model Activation	10
V.	Results and Verification	11
VI.	Parameter Sensitivity	13
VII.	Linear Optimization	17
	Tables 1 - 8	21-28
	Figures 1 - 6	29-34
	References	35
	Appendix I	37
	Appendix II	45
	Appendix III	55

ABSTRACT

A computerized steady state mathematical model which calculates dissolved oxygen levels at 16 locations in the lower Fox River and 17 locations in lower Green Bay has been developed. The oxidation-reduction factors considered in the model are BOD, nitrogen, algal respiration, bottom sludge, atmospheric reaeration, dam reaeration, and photosynthesis.

The model is activated when values for nine parameters for any particular day are inputed. These values represent DO and BOD of the source water for the Fox River from Lake Winnebago, the flow rate, water temperature, total nitrogen, chlorophyl a, and secchi readings for the Fox River and hours of daylight and month of the year for the inputed day. Winkler readings from monthly grab samples taken at 10 locations along the Fox from April, 1972 to April, 1973 verified the model accurate to within 1 ppm for the winter months and 2 ppm for the summer months for most of the sample locations.

The relative sensitivity of the nine daily inputs for the model were then statistically determined using a 2-level fraction factorial design in 16 runs with a foldover design to separate the effects and interactions. Three points of analysis were chosen. The importance of effects was found to be a function of the analysis point. Generally, temperature, chlorophyl a, turbidity, and flow were most important for the river analysis points, while month of the year, chlorophyl a, turbidity, and amount of daylight were most important for the bay analysis point.

Equations were developed to link a linear optimization computer program developed by the U.W. computing center and the DO model. This union allows the determination of the maximum BOD inputs for the 34 industrial and municipal sources of BOD along the Fox while maintaining minimum DNR DO standards in the river. Optimization runs for 6/15/72 and 8/15/72 have been made showing where BOD reductions were needed for those days to maintain minimum DO standards.

I. INTRODUCTION

The first work on the modeling of the lower Fox River from Lake Winnebago to Green Bay, Wisconsin has been attributed to the Federal Water Pollution Contr~l Administration [1]*. Since that time other models have been developed to be used for prediction of the water quality of the lower Fox River.

This work represents the construction of a dissolved oxygen model which is specifically designed to model the lower Fox River and lower Green Bay, Wisconsin for any season of the year. The need for developing a model of this scope resulted from field observations of low dissolved oxygen values in the river during the summer months and in the lower bay during the winter months of the year. In addition to dissolved oxygen modeling, management of the river and bay were also an objective of this work. In answer to this objective, the original model presented in this paper was derived and written for adaptation to linear optimization of BOD inputs to the river and statistical analysis to test the relative importance of the input parameters to the model.

This model uses some standard biological equations, improves on some assumptions and equations used in previous models and incorporates original equations concerning dam reaeration and photosynthesis. Another original aspect of this work is the application of statistical analysis and linear optimization to a dissolved oxygen model of this complexity for the purpose of water quality management.

II. COMPUTER STATIONS, FLOW TIMES

The Lower Fox River from Lake Winnebago to Green Bay has been divided into 15 segments bounded by 16 computer stations represented in Figure 1. Ten of these computer stations correspond to the grab sample locations used by Sager and Wiersma [2]. The six additional computer stations are at dam locations in the river that were not used for grab sample sites. These six additional stations were chosen for simulating the possible discontinuous increase in dissolved oxygen content of the water at these dams. A part of Lower Green Bay is also included in this computer model. The area considered is bounded on the west by the ship channel, on the north by an imaginary line between Long Tail Point and Point Au Sable, on the south and east by the shoreline of the bay. This area in the lower bay is divided into computer stations numbered 17 through 33, as shown in Figure 2. These computer stations were determined by approximating equal volumes of water and one day's flow time between the stations. The shape of the stations represent flow of water in the bay determined by conductivity tests on June 26 and July 23, 1972. These two days were relatively calm, sunny and warm.

*Numbers in brackets designate references at the end of the paper.

The volume of water between each computer station in the river was accurately calculated using the U.S. Lake Survey Chart No. 720 published by the Department of the Army Corps of Engineers. Assuming a one-dimensional flow of 1000 CFS, the flow time between each computer station in the river was easily calculated. Using a navigation chart of the lower bay, the volume of water between each bay station was accurately calculated. Assuming that the Fox River was the only input to the lower bay and one-dimensional flow prevailed, the time of flow between computer stations in the bay was easily calculated. These flow times were called ATBS in the model. The volumes and flow times between stations for 1000 CFS flow in the river are shown in Table 1. When the model is used in simulating dissolved oxygen in the river and lower bay, the flow times per 1000 CFS are adjusted by the model to correspond to the flow times of the particular day being simulated. As an example, if the river flow on a particular day is 2500 CFS the program adjusts the flow times by the factor of 1/2.5.

The location of the 34 industrial and municipal BOD inputs to the river that were considered in the model were determined with the aid of the Lake Survey Chart. Knowing the location of these inputs, the flow time of the river water, for 1000 CFS flow, from one of these inputs to the next station downstream, called ATBIS in the model, was determined. The 34 inputs considered and the values of ATBIS for each input are shown in Table 2. These flow times, corrected for actual flow rate, are then used for the highly time-dependent biological oxidation-reduction equations discussed in Section III of this paper.

III. BIOLOGICAL OXIDATION - REDUCTION FACTORS**

The basic equation in units of ppm of dissolved oxygen used in the model to calculate the dissolved oxygen at any station m is:

$$DOA_m = DOA_1 + SOURCES - SINKS \qquad (1)$$

where:

DOA_1 = dissolved oxygen content just above Station 1

SOURCES = sum of atmospheric reaeration at station m ($DOIS_m$), sum of dam reaeration at station m ($DOIC_m$), and sum of the photosynthetic activity at station m (PTC_m).

SINKS = sum of BOD oxidation at station m ($PPMC_m$), sum of total nitrogen oxidation at station m (RNC_m), sum of

**Units for constants are shown in Appendix III.

algal respiration at station m(RAC_m) and sum of

bottom sludge oxidation at station m ($RSLC_m$).

Substitution into (1) yields:

$$DOA_m = DOA_1 + DOIC_m + DOIS_m + PTC_m - PPMC_m - RNC_m - RAC_m - RSLC_m \quad (2)$$

The only sources of BOD input to the river considered in the model were Lake Winnebago and the 33 industries and municipalities in Table 2. No BOD inputs to the lower bay were considered except from the Fox River. Each industrial and municipal five-day BOD load in pounds/day was averaged for the three months of June, July, and August 1972.[3] For inputs not listed in [3], average values from [4] were used. These averaged values were used in all simulations. It was assumed the effluent was completely mixed with river water during the BOD oxidation process. These loads were converted to ppm of river water by

$$PPM_k = \frac{2(\text{BOD } \#/\text{day}) \quad (4.53 \times 10^5 \ \frac{Mg}{\#})}{Q(\frac{FT^3}{SEC}) \quad (3600 \ \frac{Sec}{HR}) \quad (24 \ \frac{HR}{DAY}) \quad (28.32 \ \frac{L}{FT^3})} \quad (3)$$

in which PPM_k is the BOD loading from industry K, Q is the river flow for the simulated day, and 2 is the average ratio of ultimate to five-day BOD Patterson [5]. The BOD oxidation equation used for each industry K was

$$PPMC_m = \sum_{k=1}^{m} [PPM_k \ (1 - e^{-(KR)TBIS_k} \ ] \quad (4)$$

where $TBIS_k$ is the flow time between industry K and station m, KR is the reaction rate from Eder [6] where

$$KR = 1.4 \times 10^{-4} \ (Q)(1.05^{(T-20)}) \quad (5)$$

in which T = water temperature in °C.

Total nitrogen values in mg/1 from 10 sampling stations on the lower Fox River [2] were used in the model for nitrification calculations. No nitrogen inputs to the lower bay were considered except from the Fox River. The nitrification equation used was

$$RNC_m = \sum_{A=1}^{m} 4.57(TNIT_A) \ (1 - e^{-1.43(KN_A)TBS_A}) \quad (6)$$

in which $TNIT_A$ is the inputed nitrogen values for each station. Field data values were used when a computer station corresponded to a field sample station and internally computed values were used when there was no correspondence, as in the bay. In these cases $TNIT_{A+1} = TNIT_A$ - amount of nitrogen oxidized between station A+1 and station A.

The rate of nitrification, 1.43 KN_A, was used in which

$$KN_A = PER_A \; (1.02^{(T-20)}). \tag{7}$$

1.43 is the maximum nitrification rate and PER_A represents percent of maximum nitrification as a function of dissolved oxygen content [6]. TBS_A in (6) represents the flow time between station A and station A+1.

Algal respiration was calculated using

$$RAC_m = \sum_{A=1}^{m} .1(PA_A)TBS_A \tag{8}$$

in which PA_A = maximum photosynthetic rate for each reach and .1 is the conversion constant for algal respiration from photosynthesis [5].

It was postulated that oxidation of bottom sludge, RSL, was related to sludge uptake, KS $\frac{gm\ O_2}{m^2 DAY}$, bottom area per reach, A, water volume per reach, VOL, flow time per reach, TBS, and a dimensional constant, K, as

$$RSL = \frac{KS(A)TBS}{VOL} (K). \tag{9}$$

Since A = WL where W = average river width per reach, L = length of reach, and VOL = WLH where H = average depth per reach, then

$$RSL = \frac{KS * TBS}{H} K \tag{10}$$

For dimensional consistency the dimensional constant

$$K = \left[\frac{gm\ O_2}{m^2 DAY}\right]\left[\frac{DAY}{FT}\right]\left[\frac{1000\ mg}{gm}\right]\left[\frac{m}{3.29\ FT}\right]\left[\frac{FT^3}{28.32\ell}\right]$$ so that

$$RSL = \frac{3.29(KS)TBS}{H} \tag{11}$$

for each reach. The temperature factor $(1.06)^{(T-20)}$ was also used [6]. Therefore total bottom sludge oxidation for any station m is represented by

$$RSLC_m = \sum_{A=1}^{m} \frac{3.29(KS)(TBS_A)(1.06)^{(T-20)}}{H_A} \tag{12}$$

Since a rather wide spectrum of values for KS pertaining to the Fox River exists in the given references, a constant value of 4.7, which is approximately an average of referenced values, was used in this model.

The dissolved oxygen increase from atmospheric reaeration, DOIA, assuming the concentration of dissolved oxygen is independent of depth Wentz [7] was derived from

$$\frac{dm}{dt} = K_L A(C_s - C_p) \tag{13}$$

in which $\frac{dm}{dt}$ = rate of O_2 mass transfer

K_L = reaeration constant

A = area of air-water interface

C_s = saturation value of dissolved oxygen

C_p = present value of dissolved oxygen

Dividing both sides of (13) by volume and setting $K_2 = \frac{K_L A}{V}$ yields

$$\frac{dc}{dt} = K_2(C_s - C_p). \tag{14}$$

Separating variables and integrating from Co to C (Co = initial value of dissolved oxygen) gives

$$C_p - Co = (C_s - Co)(1 - e^{-K_2 t}). \tag{15}$$

The dissolved oxygen increase for any reach is represented by

$$DOIA_A = (DOSAT - DOB_A)(1 - e^{-K2_A(TBS_A)}) \qquad (16)$$

where the reaeration constant

$$K2 = 2.3 \left[\frac{5.0\ U^{.97}}{H^{1.67}} \right] (1.02^{(T-20)}) \qquad (17)$$

in which U = stream velocity and H = average depth [7]. Using Q = HWU in (17) the reaeration constant for each reach is represented by

$$K2_A = \frac{11.56\ Q^{.97}}{W_A^{.97}\ H_A^{2.64}} \quad (1.02^{(T-20)}). \qquad (18)$$

The reaeration constant used for the lower bay, K2B, was found from

$$K2B = .15\ (1.02^{(T-20)}). \qquad (19)$$

(19) was used rather than (18) because of the linear relationship between W and H and Q and TBS in the bay portion of the model. The constant was determined as .15 by using typical values for Q, H, and W. The absence of atmospheric reaeration during the months when the water surface is covered with ice was approximated by setting the reaeration constant to zero for the simulated days in November, December, January, and February. The sum of atmospheric reaeration at any station m is represented by

$$DOIS_m = \sum_{A=1}^{m} DOIA_m. \qquad (20)$$

Dissolved oxygen increase from dam reaeration was used in the model. The increases from the Little Rapids and De Pere dams were determined by analysing grab samples taken above and below these dams on 1/28/72, 5/16/72, 6/15/72, 7/14/72, 8/15/72, 9/7/72, 9/20/72, and 10/19/72. It was found that the increase in dissolved oxygen could be represented by a linear relationship relating only the percent saturation of the water above and below these dams. This relationship was found to be

$$PERSB = .61(PERSA)+39 \qquad (21)$$

in which

PERSB = percent dissolved oxygen below the dams,

and PERSA = percent dissolved oxygen above the dams.

After an inspection of each lock and dam on the river, it was assumed that the reaeration characteristics of the dams at Menasha and Rapid Croche would be characterized by (21) and the dams at Appleton and Kimberly would be one-half as effective in reaeration as represented by

$$PERSB = .81(PERSA)+19.5. \qquad (22)$$

The other locks and dams were assumed to be negligible in their reaeration capabilities. Therefore the dissolved oxygen increase due to dam reaeration was found by

$$DOID = DOB - DOA \qquad (23)$$

in which the dissolved oxygen below the dam is represented by

$$DOB = PERSB(\frac{DOSAT}{100}) \qquad (24)$$

where DOSAT = saturation value of dissolved oxygen

and DOA is the dissolved oxygen content just above the dam, as calculated by the model. If no dam exists at a particular station, then DOB is set equal to DOA and therefore DOID = 0. The cumulative effect of dam reaeration at any station m is represented by

$$DOIC_m = \sum_{A=1}^{m} DOID_m \qquad (25)$$

The increase in dissolved oxygen due to photosynthesis was assumed in the model to be a function of chl α, secchi reading, temperature, water depth and hours of daylight. Assuming the photosynthetic rate [5]

$$PM = .25(CHL) \qquad (26)$$

where CHL = chlorophyll α (μg/l), then the maximum possible production rate [6]

$$PA = PM\ (1.02^{(T-20)}). \qquad (27)$$

Since the secchi readings for the river and lower bay were less than the depth, it was assumed that the mass of water below the secchi value was not oxygen productive due to photosynthesis. It was further assumed that photosynthetic production decreased linearly from a maximum at the surface to zero at the secchi depth. Therefore the average value of production

$$PQ = \frac{PA(C)}{2H} \qquad (28)$$

in which C = secchi reading (meters). The production rate as a function of sunlight intensity at the water surface was represented by

$$\frac{PT}{TIME} = K(DL) \int_{0}^{\pi} PQ \sin x dx \tag{29}$$

or

$$\frac{PT}{TIME} = 2K(DL)\ PQ \tag{30}$$

in which DL = hours of daylight and $K = \frac{1}{12}$.

The addition of oxygen due to photosynthesis per reach is therefore

$$PT_A = (\frac{1}{6})\ (PQ_A)\ (DL)(TBS_A) \tag{31}$$

and the cumulative sum at any station m is

$$PTC_m = \sum_{A=1}^{m} PT_A. \tag{32}$$

IV. MODEL ACTIVATION

The dissolved oxygen model for the lower Fox River and lower Green Bay is represented by the computer program shown in Appendix 1. It was written in the Fortran IV language, stored on disc and can be run with either a portable teletypewriter or punched cards. Previously defined data values and constants are also stored on disc. These include 33 values of BOD, 33 values of ATBS, 34 values of ATBIS, 15 values of PER (which represents a table of percentage of maximum nitrification rates), 50 values of DOSAT (which represents a saturation table of dissolved oxygen as a function of temperature), 32 values of H, 15 values of W and KS.

When an individual, using a teletypewriter, activates the model to simulate a particular day, the teletype responds with "ENTER Q, DOA(1), TEMP, PPM(1), DL, and MONTH (one value per line followed by carriage a return)." The values requested are data for the particular day to be simulated by the model. They are the flow rate of the river, the dissolved oxygen content of the water just above Station No. 1, the water temperature of the river, the value of BOD in the water just above Station 1, the number of hours of daylight, and the month of the year. After these values are inputed by the operator the teletypewriter responds with "NOW ENTER THE AVERAGE OF 10 TNIT VALUES." The 10 TNIT values refered to are the total nitrogen values [2] from the 10 sampling stations along the Fox River. The program was originally written and can be easily changed to accept each value rather than the average of the values. It was found that the model results were affected only slightly when an average value of the 10 was used instead of the individual 10 values. Therefore, to conserve operator time, the average value was used. After the average of the total nitrogen values are entered by the operator, the teletypewriter responds with "NOW ENTER THE AVERAGE OF 10 CHL VALUES." These values are the chlorophyll a values from the 10 sampling stations along the river. Once again the average value was used for the same reasons as above. After this chlorophyll a value is entered by the operator the teletypewriter responds with "NOW ENTER THE AVERAGE OF 10 C (SECCHI) VALUES". These 10 values refer to the secchi readings at the 10 sample stations and again the average value is used for the above reasons. After the operator enters this value the computer commences to calculate and print the dissolved oxygen value at all the computer stations in the lower Fox River and lower bay. After the printout of these values the operator may simulate another day by typing the word "RUN" after which the teletypewriter will respond with "ENTER Q, DOA(1), etc." repeating the whole process with the values of the next day to be simulated.

The amount of time needed for the operator to simulate one day's run with this program is approximately two minutes. Therefore, if the operator has at his disposal the adequate data, he can simulate several days in a short period of time. After exhaustion of either the data or the operator, the operator stops the simulation process by typing "BYE."

V. RESULTS AND VERIFICATION

Twelve simulation runs were made representing one day of each month from April, 1972 through March, 1973, corresponding to those days in which grab sample dissolved oxygen values were available for the river [2]. Figures 3-6 show the dissolved oxygen values predicted by the model for each computer station and the dissolved oxygen values as determined by laboratory tests from grab samples at the 10 sampling stations. Unfortunately, no laboratory data was available for the computer stations in the lower bay for the simulated days, and therefore no verification of the dissolved oxygen values in the lower bay was available.

Comparison of the model values and the laboratory values shows relatively good agreement throughout most of the year. A notable exception, however, occurred in the simulation for July 14, 1972, in which the model results differed greatly from the laboratory results. The reason for this large discrepancy in values is at this time unknown. As shown by Figures 3-6, the best agreement occurs for the simulated runs representing April 4, 1972; Sept. 20, 1972; October 19, 1972; Dec. 26, 1972; Jan. 23, 1973; Feb. 20, 1973; and March 6, 1973, in which the model and laboratory values agreed within 1.2 parts per million for all stations. The greatest variation for the May 3, 1972 simulation was 2.2 parts per million; for June 15, 1972 - four parts per million; for July 14, 1972 - 4.8 parts per million; and for August 15, 1972 - 4.2 parts per million. The simulated results for November 28, 1972 were generally one part per million below the laboratory results for most of the stations with the exception of Station 16, in which the discrepancy was 3.8 parts per million.

After analysing the results of the river portion of the model, it appeared that the model simulates the river conditions very closely for the cold months of the year and the model simulation is adequate except for the July 14, 1972 run during the warm months of the year. During the cold months of the year the river is at or near saturation, and therefore the dam reaeration effects are small. Also, since the water temperature is low the biological rates are small. Therefore dissolved oxygen values are changing slowly and steady state model simulation is relatively accurate. During the warm months of the year the water temperature is high and the biological rates are large. The percent saturation of dissolved oxygen in the water is low, and therefore the effect of dam reaeration is great. Most importantly, photosynthesis has been shown to be very large based on continuously monitored dissolved oxygen values in the river at the Wisconsin Public Service Pulliam Plant Wiersma[8]. This study has shown that on warm, sunny days the dissolved oxygen content can be more than doubled by photosynthesis during the day. Therefore, the time of day that the laboratory grab sample was taken is an important factor in the dissolved oxygen content at the sampling site. These effects are difficult to simulate with a steady state model, and therefore the prediction of dissolved oxygen at a station during this time of year is relatively inaccurate.

After analysing the results of the bay portion of the model it appeared that three distinct types of interactions between dissolved oxygen addition and reduction are shown in Figures 3-6. In the first type of interaction which occurred for the June, July, and August simulation, the bay water becomes anaerobic and then aerobic again at a later station. These results dramatize the high rate of oxidation in reducing the latent BOD content in the water finally being offset by the oxygen additions from photosynthesis and atmospheric reaeration.

The second type of interaction which occurred for the March, April, May, September, and October simulations is represented by the dissolved oxygen being reduced, reaching a minimum aerobic value and then increasing at later stations. These results show a reduced rate of oxidation in reducing the latest BOD content in the water due to lower water temperature being offset by the photosynthetic and atmospheric oxygen additions.

The third type of interaction which occurred for the November, December, January, and February simulations is represented by a constant decrease in dissolved oxygen to the northern limits of the model. This effect is affected by the slow rate of oxidation of latent BOD and the absence of atmospheric reaeration due to ice cover on the bay.

These twelve simulation runs demonstrate the ability of this model to predict the dissolved oxygen content in the lower Fox River and lower bay at any time of the year within the accuracy implied by the results shown in Figures 3-6.

VI. PARAMETER SENSITIVITY

A two-level fractional factorial design was performed on the model in which the relative importance of the nine parameters read into the teletypewriter was determined. Since a full factorial design in nine variables requires 2^9 or 512 runs, which was not economically justifiable for this experiment, a two-level fractional factorial design in 16 runs was chosen. This requires that five generators must be defined according to

$$R = 2^{(K-P)} \qquad (33)$$

where
R = number of runs
K = number of variables
P = number of generators

The levels for each variable used in the analysis are shown in Table 3. The design matrix with coded variable levels is shown in Table 4. Columns 5, 6, 7, 8, and 9 were generated from columns 1, 2, 3, and 4, as shown in the table. The first generator, I_1, was formed by Column 5 resulting in $I_1 = 1.3.5$. Similarly $I_2 = 1.2.3.6$, $I_3 = 2.3.4.7$, $I_4 = 1.3.4.8$, and $I_5 = 1.2.3.4.9$.

The defining relation was found by multiplying all possible combinations of the generators one, two, three, four, and five at a time as follows:

I = 135 = 1236 = 2347 = 1348 = 12349 (one at a time)
= 256 = 12457 = 458 = 2459 = 1467 = 2468 = 469 = 1278 = 179 = 289 (two at a time)
= 34567, etc. (three at a time)
= 15678, etc. (four at a time)
= 23456789 (five at a time)

The 16 runs were made using the high and low values for the 9 variables. Three outputs were calculated by the model corresponding to the dissolved oxygen at the mouth of the river, y_1, the dissolved oxygen at Station 32,

y_2, and the dissolved oxygen at Station 10, y_3. The data matrix and the results from the model at these three stations are shown in Table 5. Assuming three-factor and higher interactions negligible, the effects and interactions were found by adding the model results and dividing by the number of positive signs in the appropriate unit column. Negative model results were assigned a value of zero based on physical considerations. Therefore, from the results at the mouth of the river, y_1,

$$L_1 = 1 + 35 + 79 = \frac{20.3}{8} = 2.5$$

$$L_2 = 2 + 56 + 89 = \frac{8.9}{8} = 1.1$$

Similarly,

$$L_3 = -6.1$$

$$L_4 = 0$$

$$L_5 = .8$$

$$L_6 = .4$$

$$L_7 = -.4$$

$$L_8 = 1.1$$

$$L_9 = 1.2$$

In order to separate the effects and interactions a fold-over design was performed. The fold-over design matrix is shown in Table 6, and the fold-over data matrix with the output values computed by the model are shown in Table 7. Therefore, from the fold-over design

$$L_1' = 1 - 35 - 79 = \frac{21.2}{8} = 2.7$$

$$L_2' = 2 - 56 - 89 = \frac{-6.8}{8} = -.8$$

Similarly,

$$L_3' = -6.$$

$$L_4' = -.8$$

$$L_5' = .3$$

$$L_6' = .4$$

$$L_7' = .1$$

$L_8' = 1.1$

$L_9' = 1.4$

The results of the two designs were combined yielding

$$E_1 = \tfrac{1}{2}(L_1 + L_1') = \tfrac{1}{2}(2.5 + 2.7) = 2.6$$

and

$$E_{35+79} = \tfrac{1}{2}(L_1 - L_1') = \tfrac{1}{2}(2.5 - 2.7) = -.1$$

The complete results are:

EFFECTS	INTERACTIONS
$E_1 = 2.6$	$E_{35+79} = -.1$
$E_2 = .2$	$E_{56+89} = 1.0$
$E_3 = -6.1$	$E_{15} = -.1$
$E_4 = -.4$	$E_{58+69} = .4$
$E_5 = .6$	$E_{13+26+48} = .3$
$E_6 = .4$	$E_{25+49} = 0$
$E_7 = -.2$	$E_{19} = -.3$
$E_8 = 1.1$	$E_{45+29} = 0$
$E_9 = 1.3$	$E_{46+28} = -.1$

Based on this limited analysis, it is seen that water temperature is the most important parameter, flow rate is second in importance, turbidity is third, and chlorophyll a is fourth. From the calculations of interactions it is seen that the most important interaction is 56 + 89. The other interactions are of much lesser importance.

A similar analysis was performed for the last station in the bay, Station 32, with the following results:

EFFECTS	INTERACTIONS
$E_1 = .1$	$E_{35+79} = -.2$
$E_2 = .3$	$E_{56+89} = 4.3$

$E_3 = -.5$		E_{15}	$= -.1$
$E_4 = -.7$		E_{58+69}	$= 1.5$
$E_5 = 1.3$		$E_{13+26+48}$	$= 1.3$
$E_6 = 5.7$		E_{25+49}	$= -.1$
$E_7 = .5$		E_{19}	$= .1$
$E_8 = 5.3$		E_{45+29}	$= .3$
$E_9 = 4.8$		E_{46+28}	$= .2$

The results of this analysis show the month of the year, the chlorophyll a concentration and the turbidity of the water are almost equally important and the hours of daylight is relatively small in importance. The most important interactive effects are between variables 56+89 and 58+69.

A similar analysis was performed for an intermediate station in the river, Station 10, with the following results:

EFFECTS	INTERACTIONS	
$E_1 = .7$	E_{35+79}	$= .1$
$E_2 = .6$	E_{56+89}	$= 1.1$
$E_3 = -4.5$	E_{15}	$= -.1$
$E_4 = -.8$	E_{58+69}	$= .4$
$E_5 = .7$	$E_{13+26+48}$	$= .3$
$E_6 = .6$	E_{25+49}	$= 0$
$E_7 = -.3$	E_{19}	$= -.5$
$E_8 = 2.6$	E_{45+29}	$= 0$
$E_9 = 1.6$	E_{46+28}	$= .2$

This analysis shows water temperature is the most important, chlorophyll a is second in importance, turbidity is third, and flow and amount of daylight are both fourth. The interactive effect between 56+89 is somewhat important while the others are somewhat minor.

Past results of water analysis of the Fox River has shown that low dissolved oxygen values usually occur during low flow periods; however, these periods usually correspond to high water temperatures. Separation of these two effects in this analysis shows the importance of water temperature and relative unimportance of flow rate for the water quality of the Fox River to Station 10. The implication of these results relate to the theory of low flow augmentation in that a reasonable increase in water quality does not result from increasing the flow rate of the river, but results from a drop in water temperature during flow augmentation. This temperature drop could be the result of using Lake Winnebago water which has a lower temperature than the river water, compounded by reducing the effect of solar heating, which is increased by stagnation of the river.

The relative importance of flow rate increases between Station 10 and Station 16, but still remains less than water temperature. This change could be caused from a decrease in surface area and an increase in depth of the river for this reach, thereby decreasing the mass of water subject to photosynthesis which increased the relative importance of flow rate. Since temperature and flow rate are the two most important effects for this reach, flow augmentation would be more effective in increasing the water quality in this portion of the river than in the upper portion.

The most important parameters that influence the water quality in the lower bay are those related to atmospheric reaeration and photosynthesis. The parameter, month of the year, which is related to atmospheric reaeration, is shown to be the most important effect. This reflects the major importance of the ice cover on the bay during the winter months which retards the improvement of the water quality in the bay during this time of the year.

The next three most important parameters, chlorophyll a, turbidity, and hours of daylight are related to photosynthetic activity. This reflects the major importance of photosynthesis in the improvement of the water quality in the bay from depressed dissolved oxygen values at the mouth of the Fox River.

VII. LINEAR OPTIMIZATION

A linear optimization subroutine available at the computing center in Madison, Wisconsin was used in conjunction with the DO model to maximize the BOD inputs to the river from the 34 municipal and industrial inputs, while maintaining minimum DNR standards for dissolved oxygen of 5 parts per million in the upper section of the Fox River to Wrightstown, and 2 parts per million in the lower section of the Fox River and lower Green Bay. Although the union of the linear programming subroutine and the DO model was successful, it was not possible to run the optimization routine with the teletypewriter unit located in Green Bay because of the difficulties in linking the computer at Green Bay to the computer at Madison. Therefore, to run an optimization of a simulated day the program shown in Appendix II was read into the machine with punched cards in Green Bay, sent to Madison for calculation, and the results sent back to Green Bay. Therefore, unlike the very rapid and cheap simulation of dissolved oxygen in the river using the teletypewriter, the linear optimization run was rather time consuming and somewhat expensive.

In order to successfully link the duplex subroutine to the dissolved oxygen model a few matrices had to be derived. The 15 unknowns in the objective functions to be maximized by the routine were arranged in a 15 x 1 vector called the DPS array represented by

$$DPS(M) = \sum_{J=N}^{L} PPM(J) \tag{34}$$

in which N = the identifying number of the first BOD input in the M^{th} section of the river, and L = the identifying number of the last input in the M^{th} section of the river. If a K^{th} section of the river does not contain any BOD inputs, the value for DPS(K) was set equal to zero. The next derived array was a 15 x 34 matrix which was called the D array, or the penalty factor array, which is represented by

$$D(I,J) = \sum_{I=1}^{15} \sum_{J=1}^{34} \frac{PPM(J)}{DPS(I)} \tag{35}$$

in which I = a river section and J = an identifying number of the input. This matrix, which is part of the constraints, proportions the liability of each input for each section of the river. For instance, if an input was responsible for 40% of the DPS in a particular reach of the river, the duplex subroutine limits the industry to no more than 40% of the optimum DPS calculated by the duplex routine. The locations in the D matrix that represent river reaches where BOD inputs do not exist were set to zero. The third derived array is the P(K,J) array which is called the fraction oxidized array. It is a 32 x 34 matrix representing the 15 river and 17 bay stations and the 34 BOD inputs to the river. This array represents the fraction of the total amount of BOD from input J which has been oxidized at Station (K+1). As an example, P(1,1) is equal to the fraction of BOD oxidized from input 1 at Station 2 and P(32,34) equals the fraction of BOD oxidized from input 34 at Station 33. Due to the highly complex way in which the matrix is linked with the DO model, it is best represented by computer statements 260-298 in the program shown in Appendix II. The fourth array is a 64 x 32 matrix which is a combination of the D and P matrices called the A matrix. This matrix represents the constraints for the problem. The first 32 rows of the A matrix are the coefficients from D x P on the unknowns to be maximized, and the next 32 rows represent constraints which limit the inputs to being less than or equal to the present DPS. Again, due to the complex union of these equations and the DO model, they are best represented by computer statements 405-446 in Appendix II. The last derived array is a 64 x 1 vector called the RHS array, or the right hand side array. The values in this array represent the boundary conditions which the unknowns in the A matrix must satisfy. This array is calculated in three parts. The first eleven rows are represented by

$$RHS(M) = DOA(M+1) + PPMC(M) - 5 \qquad M = 1, 11 \tag{36}$$

in which a minimum dissolved oxygen level of 5 parts per million was assumed between Stations 1 - 11, or from Lake Winnebago to Wrightstown. The next 21 rows are represented by

$$RHS(M) = DOA(M+1) + PPMC(M) - 2 \qquad M = 12, 32 \tag{37}$$

in which a minimum dissolved oxygen level of 2 parts per million was assumed between Wrightstown and the northern-most station in the bay. The last 32 rows in the RHS array are represented by

$$RHS(M) = DPA(M-32) \qquad M = 33, 64 \tag{38}$$

which limit the unknowns in the A matrix to be less than or equal to the input DPS. The other arrays in the program were used for the initialization and output format of the duplex subroutine.

Two optimization runs were made for the simulations of June 15, 1972 and August 15, 1972. The results for the June 15 simulation showed that a 39% decrease in the BOD inputs between Station 1 and Station 2 should have been made to maintain minimum DNR water quality standards in the river and lower bay. Reductions of BOD inputs in all other section of the river were not needed. Referring to the DO profile of June 15 shown in Figure 3, it can be seen that the dissolved oxygen decreases from approximately 10 parts per million at Station 1 to 2 parts per million at Station 5. Since there are no major inputs between Stations 2 and 5, it is assumed that the depression in dissolved oxygen is still continuing from the effect of inputs between Station 1 and 2. Note also that the average dissolved oxygen from Station 5 to Station 14 is increasing slightly. Therefore the optimization results indicate, in effect, that if the dissolved oxygen at Station 5 were raised to a greater value, the effect of the other inputs to the river below Station 5 would not decrease the dissolved oxygen to below minimum standards.

The optimization results for the August 15 simulation showed that a 52% decrease in the BOD inputs between Stations 11 and 12 should have been made to maintain minimum DO standards. Reductions of BOD inputs in all other sections of the river were not needed. Referring to the DO profile of August 15 in Figure 4, it can be seen that the dissolved oxygen content of the river is decreasing to 3 parts per million at Station 11 after which there are large oscillations of dissolved oxygen from Stations 11 to 14. Since the only major input to the river between Stations 11 and 14 is between Stations 11 and 12, it is assumed that this input is causing the rapid depression of dissolved oxygen between Stations 11 and 14, while the rapid increase in dissolved oxygen is caused by dam reaeration at Stations 12, 13, and 14. The optimization results indicate that if the BOD inputs between Stations 11 and 12 were reduced by 52% the dissolved oxygen between Stations 11 and 12 would increase due to dam reaeration, and therefore the other inputs to the river below Station 14 would not depress the dissolved oxygen level below acceptable standards.

Table 8 shows the municipal and industrial inputs between Sections 1 and 2, and 11 and 12, the penalty factors for each input, and the percent reduction in BOD for each input for the two simulated days. As seen in this table, major reductions in the BOD inputs from Lake Winnebago and Bergstrom Paper Company were needed for the June 15 simulation, while a major BOD reduction from Thilmany Pulp and Paper Company was needed for the August 15 simulation to maintain minimum standards in the river and lower bay.

The results of the optimization of these two simulated days have demonstrated the applicability of this program to the management of water quality in the lower Fox River and lower Green Bay. The ability of this program to assess liability for the depression in water quality caused by the industrial and municipal sources of BOD discharge to the river using scientific methods is unique. The amount of field data needed to affect the results of this program is relatively small, and considering the significance of the results, the expenditure in time and money to obtain these data are certainly justified.

TABLE 1

FLOW TIME BETWEEN STATIONS FOR 1000 CFS FLOW

Computer Stations	Water Volume ($X10^8$ FT^3)	ATBS (Days)
1-2	2.36	2.73
2-3	.48	.56
3-4	.05	.06
4-5	.12	.14
5-6	.69	.80
6-7	.16	.18
7-8	.34	.39
8-9	.39	.45
9-10	.01	.01
10-11	.01	.01
11-12	1.11	1.29
12-13	1.10	1.27
13-14	2.13	2.47
14-15	2.46	2.85
15-16	2.49	2.88
16-17	1.33	1.54
17-18	1.24	1.43
18-19	1.77	2.06
19-20	2.09	2.42
20-21	1.83	2.12
21-22	1.91	2.22
22-23	1.86	2.16
23-24	1.97	2.28
24-25	2.30	2.66
25-26	2.23	2.58
26-27	2.03	2.35
27-28	2.30	2.66
28-29	1.90	2.20
29-30	1.83	2.12
30-31	1.55	1.80
31-32	1.94	2.24
32-33	1.40	1.62

TABLE 2

INPUT LOCATIONS ON THE LOWER FOX RIVER
AND FLOW TIMES FOR 1000 CFS FLOW

No.	Input	Between Station	Mile Pt.	ATBIS (Days)
1.	Lake Winnebago	1-2	38.5	2.73
2.	K-C (Neenah)	1-2	38.5	2.73
3.	K-C (Badger Globe)	1-2	38.4	2.72
4.	Gilbert Paper	1-2	38.3	2.72
5.	John Strange	1-2	38.2	2.72
6.	Bergstrom	1-2	38.2	2.72
7.	K-C STP	1-2	38.2	2.72
8.	K-C (Lakeview)	1-2	37.9	2.60
9.	Neenah-Menasha, City	1-2	37.8	2.56
10.	G. A. Whiting	1-2	37.5	2.26
11.	Menasha, Town of	1-2	36.0	.82
12.	Holiday Inn	1-2	35.8	.27
13.	Riverside Paper	4-5	32.2	.10
14.	Foremost Foods	4-5	31.5	.00
15.	Consolidated Paper	5-6	31.2	.76
16.	Appleton, City of	5-6	30.4	.58
17.	K-C (Kimberly)	6-7	27.9	.18
18.	Kimberly, Village of	7-8	27.0	.39
19.	Combined Paper	8-9	26.2	.45
20.	Little Chute, Village	8-9	26.0	.44
21.	Kaukauna, City of	11-12	23.7	1.29
22.	Thilmany	11-12	23.6	1.23
23.	Wrightstown, Village	12-13	17.6	1.00
24.	Charmin Paper	13-14	13.3	2.47
25.	Hickory Grove Sanatorium	13-14	12.2	2.21
26.	Nicolet Paper	14-15	7.1	2.81
27.	U.S. Paper	14-15	6.9	2.51
28.	De Pere, City of	14-15	6.1	2.16
29.	Fort Howard	14-15	3.7	.88
30.	Fort Howard STP	14-15	3.6	.88
31.	American Can	15-16	1.2	1.38
32.	Charmin	15-16	1.0	1.23
33.	G. B. Packaging	15-16	.7	.99
34.	G. B. MSD	15-16	.1	.35

TABLE 3

LEVELS OF INPUT VARIABLES

Computer Variable	High (+1)	Low (-1)
1. Q	5000	2800
2. DOA(1)	12	10
3. TEMP	19	4
4. PPM(1)	4	1.5
5. DL	14	10
6. MONTH	5	2
7. TNIT	.7	.4
8. CHL	40	7
9. C	1	.5

TABLE 4

STATISTICAL DESIGN MATRIX

Run	1.	2.	3.	4.	Variable				
					5=13	6=123	7=234	8=134	9=1234
1	-1	-1	-1	-1	+1	-1	-1	-1	+1
2	+1	-1	-1	-1	-1	+1	-1	+1	-1
3	-1	+1	-1	-1	+1	+1	+1	-1	-1
4	+1	+1	-1	-1	-1	-1	+1	+1	+1
5	-1	-1	+1	-1	-1	+1	+1	+1	-1
6	+1	-1	+1	-1	+1	-1	+1	-1	+1
7	-1	+1	+1	-1	-1	-1	-1	+1	+1
8	+1	+1	+1	-1	+1	+1	-1	-1	-1
9	-1	-1	-1	+1	+1	-1	+1	+1	-1
10	+1	-1	-1	+1	-1	+1	+1	-1	+1
11	-1	+1	-1	+1	+1	+1	-1	+1	+1
12	+1	+1	-1	+1	-1	-1	-1	-1	-1
13	-1	-1	+1	+1	-1	+1	-1	-1	+1
14	+1	-1	+1	+1	+1	-1	-1	+1	-1
15	-1	+1	+1	+1	-1	-1	+1	-1	-1
16	+1	+1	+1	+1	+1	+1	+1	+1	+1

TABLE 5

DATA MATRIX

Run	Variable 1.	2.	3.	4.	5.	6.	7.	8.	9.	Output Y_1	Y_2	Y_3
1	2800.	10.	4.0	1.5	14.	2.0	.4	7.0	1.0	6.9	-3.5	10.2
2	5000.	10.	4.0	1.5	10.	5.0	.4	40.0	.5	9.3	6.6	11.7
3	2800.	12.	4.0	1.5	14.	5.0	.7	7.0	.5	6.4	4.7	10.7
4	5000.	12.	4.0	1.5	10.	2.0	.7	40.0	1.0	10.3	8.9	13.4
5	2800.	10.	19.0	1.5	10.	5.0	.7	40.0	.5	-1.4	4.8	6.3
6	5000.	10.	19.0	1.5	14.	2.0	.7	7.0	1.0	3.2	-.6	6.7
7	2800.	12.	19.0	1.5	10.	2.0	.4	40.0	1.0	2.0	8.9	10.3
8	5000.	12.	19.0	1.5	14.	5.0	.4	7.0	.5	3.6	4.2	7.4
9	2800.	10.	4.0	4.0	14.	2.0	.7	40.0	.5	6.1	-2.0	11.1
10	5000.	10.	4.0	4.0	10.	5.0	.7	7.0	1.0	8.6	5.3	10.8
11	2800.	12.	4.0	4.0	14.	5.0	.4	40.0	1.0	10.0	18.0	15.5
12	5000.	12.	4.0	4.0	10.	2.0	.4	7.0	.5	8.3	-.9	10.6
13	2800.	10.	19.0	4.0	10.	5.0	.4	7.0	1.0	-1.0	5.4	4.9
14	5000.	10.	19.0	4.0	14.	2.0	.4	40.0	.5	3.0	1.4	7.2
15	2800.	12.	19.0	4.0	10.	2.0	.7	7.0	.5	-2.8	-14.2	3.5
16	5000.	12.	19.0	4.0	14.	5.0	.7	40.0	1.0	5.4	14.7	10.1

TABLE 6

FOLDOVER DESIGN MATRIX

Run	1	2	3	4	Variance				
					5=-13	6=-123	7=-234	8=-134	9=-1234
17	+1	+1	+1	+1	-1	+1	+1	+1	-1
18	-1	+1	+1	+1	+1	-1	+1	-1	+1
19	+1	-1	+1	+1	-1	-1	-1	+1	+1
20	-1	-1	+1	+1	+1	+1	-1	-1	-1
21	+1	+1	-1	+1	+1	-1	-1	-1	+1
22	-1	+1	-1	+1	-1	+1	-1	+1	-1
23	+1	-1	-1	+1	+1	+1	+1	-1	-1
24	-1	-1	-1	+1	-1	-1	+1	+1	+1
25	+1	+1	+1	-1	-1	+1	-1	-1	+1
26	-1	+1	+1	-1	+1	-1	-1	+1	-1
27	+1	-1	+1	-1	-1	-1	+1	-1	-1
28	-1	-1	+1	-1	+1	+1	+1	+1	+1
29	+1	+1	-1	-1	+1	-1	+1	+1	-1
30	-1	+1	-1	-1	-1	+1	+1	-1	+1
31	+1	-1	-1	-1	+1	+1	-1	+1	+1
32	-1	-1	-1	-1	-1	-1	-1	-1	-1

TABLE 7 - FOLDOVER DATA MATRIX

Run	Variable									Output		
	1	2	3	4	5	6	7	8	9	Y1	Y2	Y3
17	5000.	12.	19.	4.	10.	5.	.7	40.	.5	2.5	3.9	7.3
18	2800.	12.	19.	4.	14.	2.	.7	7.	1.0	-1.8	-8.2	4.7
19	5000.	10.	19.	4.	10.	2.	.4	40.	1.0	4.2	7.3	8.4
20	2800.	10.	19.	4.	14.	5.	.4	7.	.5	-1.3	4.6	4.6
21	5000.	12.	4.	4.	14.	2.	.4	7.	1.0	8.8	1.4	11.1
22	2800	12.	4.	4.	10.	5.	.4	40.	.5	6.0	5.3	11.4
23	5000.	10.	4.	4.	14.	5.	.7	7.	.5	8.4	4.8	10.7
24	2800.	10.	4.	4.	10.	2.	.7	40.	1.0	7.7	5.4	12.8
25	5000.	12.	19.	1.5	10.	5.	.4	7.	1.0	3.8	4.8	7.5
26	2800.	12.	19.	1.5	14.	2.	.4	40.	.5	-0.0	-1.5	8.1
27	5000.	10.	19.	1.5	10.	2.	.7	7.	.5	2.6	-3.9	6.1
28	2800.	10.	19.	1.5	14.	5.	.7	40.	1.0	3.6	18.9	11.4
29	5000.	12.	4.	1.5	14.	2.	.7	40.	.5	9.5	4.1	12.4
30	2800.	12.	4.	1.5	10.	5.	.7	7.	1.0	6.7	5.4	10.9
31	5000.	10.	4.	1.5	14.	5.	.4	40.	1.0	11.5	16.0	14.0
32	2800.	10.	4.	1.5	10.	2.	.4	7.	.5	6.1	-7.9	9.3

TABLE 8

RESULTS OF BOD OPTIMIZATION

Date	Input	Penalty Factor (%)	Absolute BOD Reduction (%)
6/15/72	Lake Winnebago	57.8	22.5
	K. C. (Neenah)	.1	< .1
	K. C. (Badger-Globe)	.2	< .1
	Gilbert Paper	< .1	< .1
	John Strange	1.2	.5
	Bergstrom Paper	29.2	11.4
	K. C. STP	< .1	< .1
	K. C. (Lakeview)	.8	.3
	Neenah-Menasha Sewage District	9.8	3.8
	Whiting	.3	.1
	Menasha, Town of	.2	< .1
	Holiday Inn	< .1	< .1
8/15/72	Thilmany Pulp & Paper	99.1	51.5
	Kaukauna, City of	.9	.7

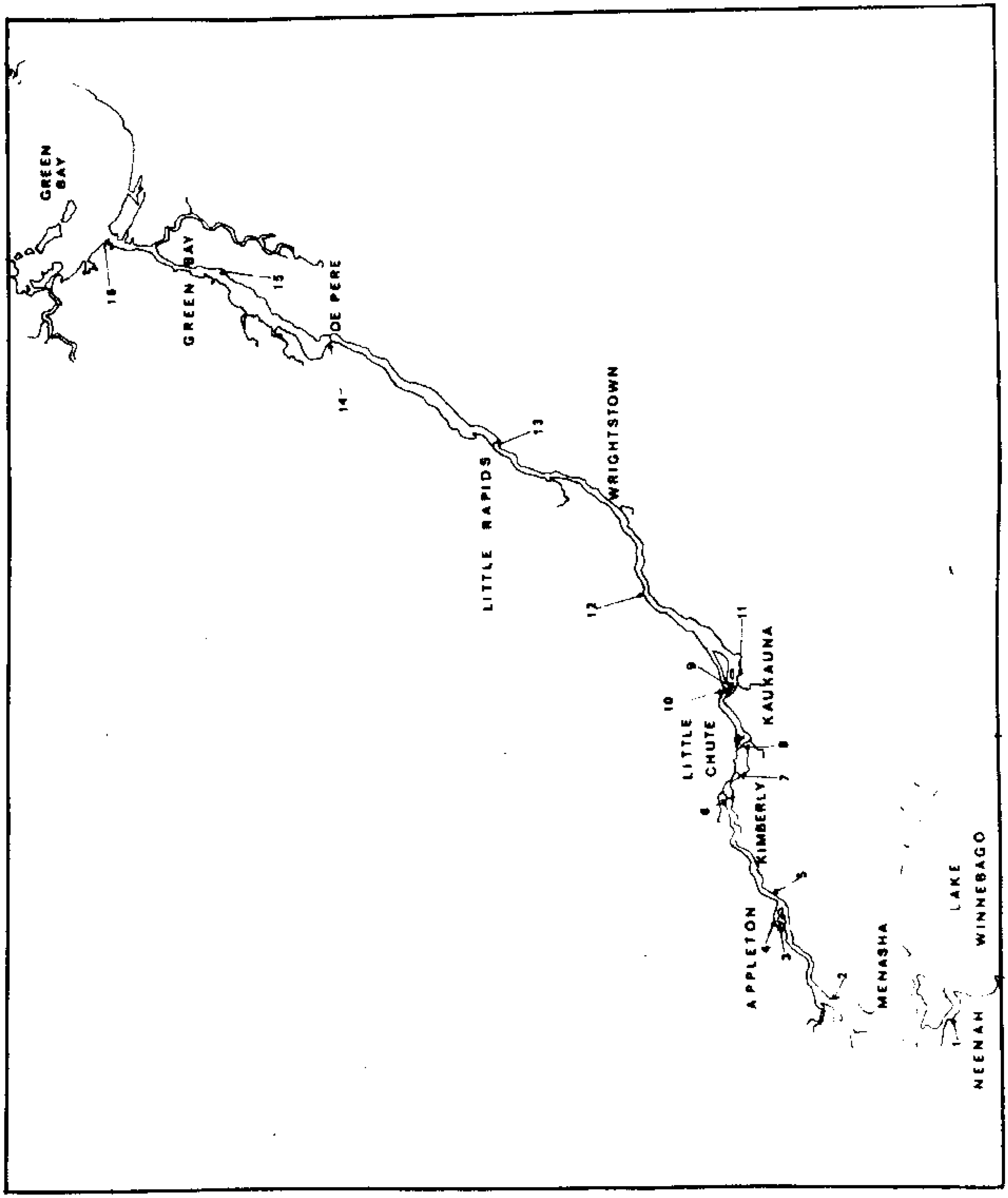

FIGURE 1 - COMPUTER STATIONS ON LOWER FOX RIVER

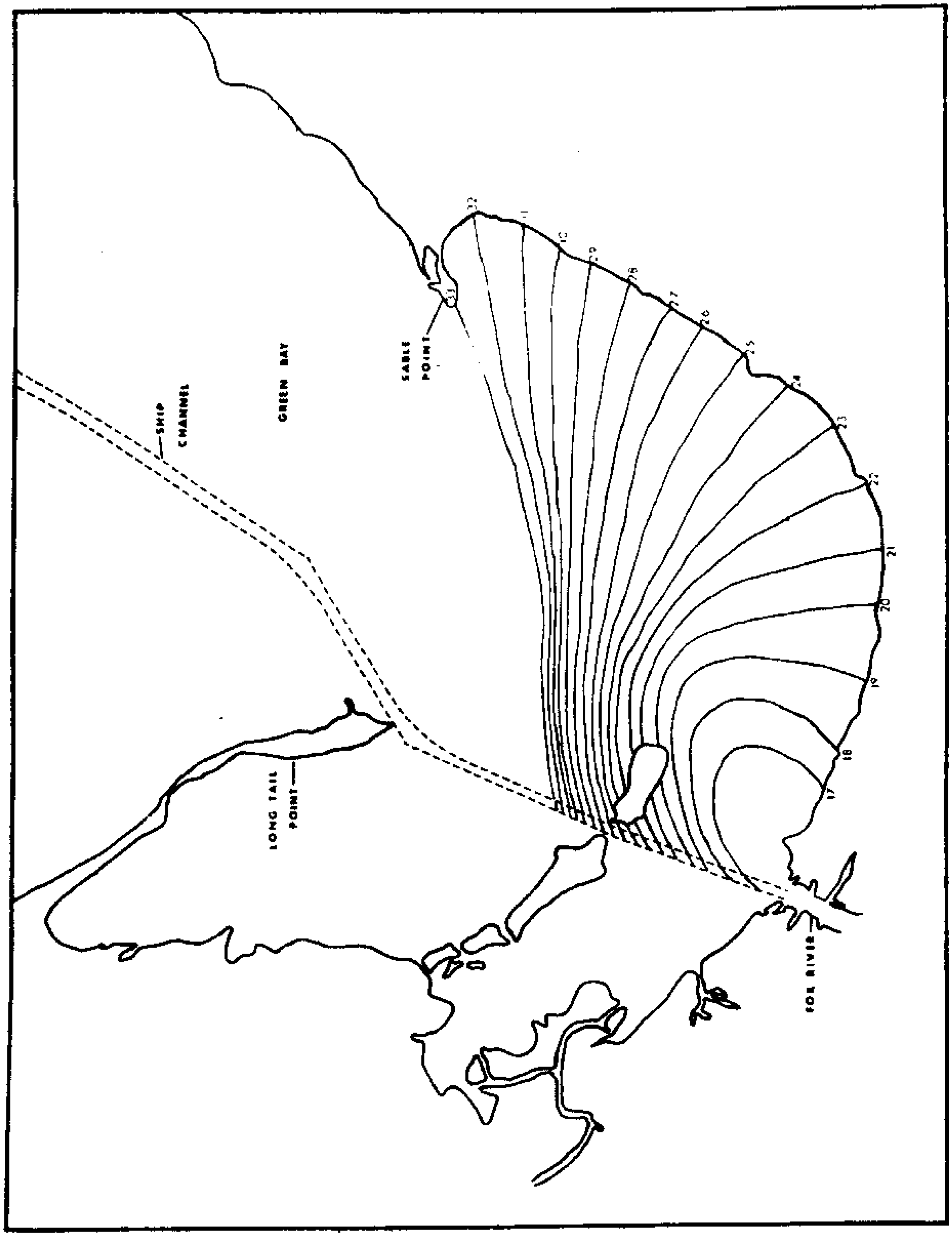

FIGURE 2 - COMPUTER STATIONS IN LOWER GREEN BAY

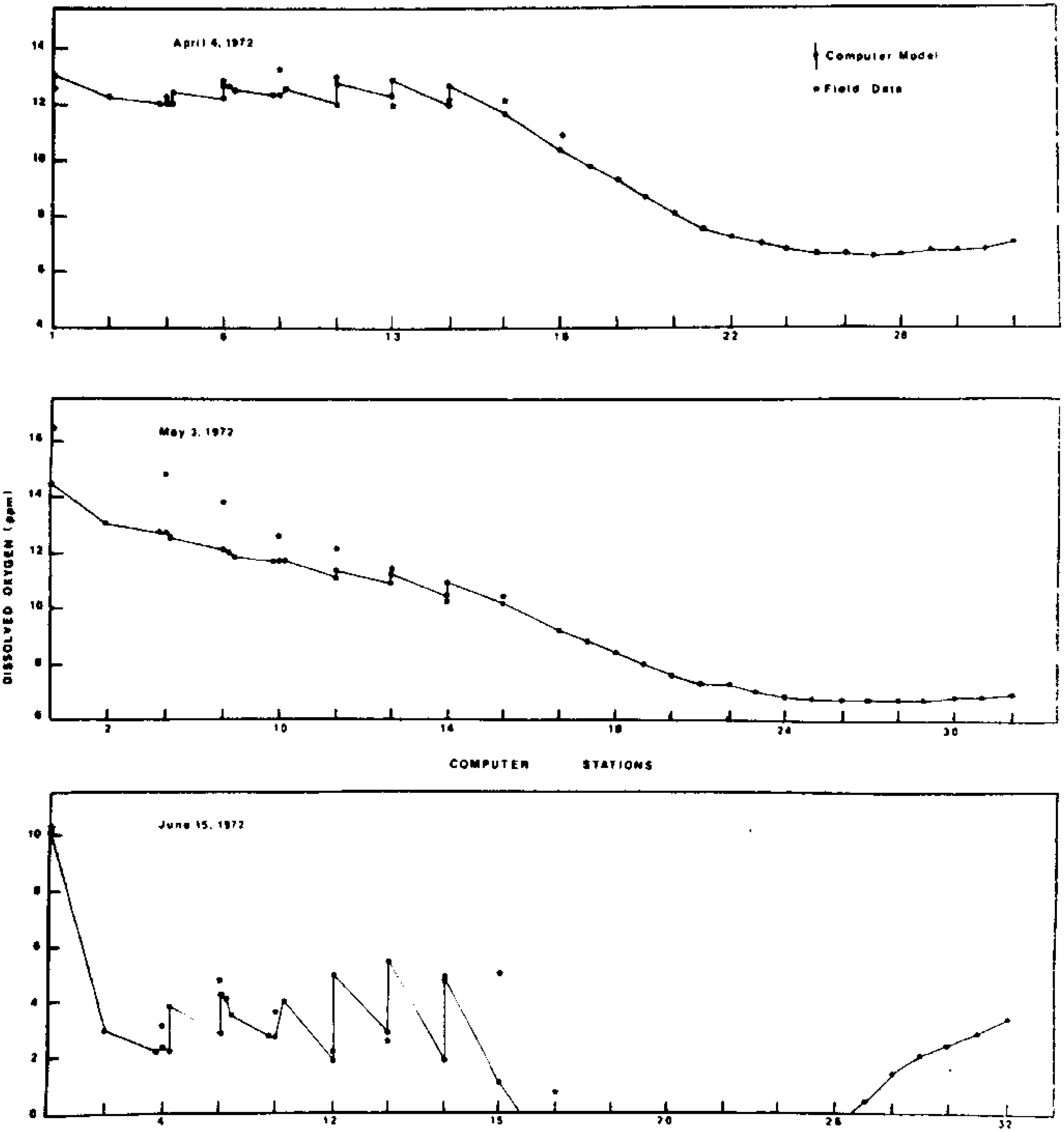

FIGURE 3 - VERIFICATION OF COMPUTER MODEL BY DISCRETE FIELD DATA VALUES

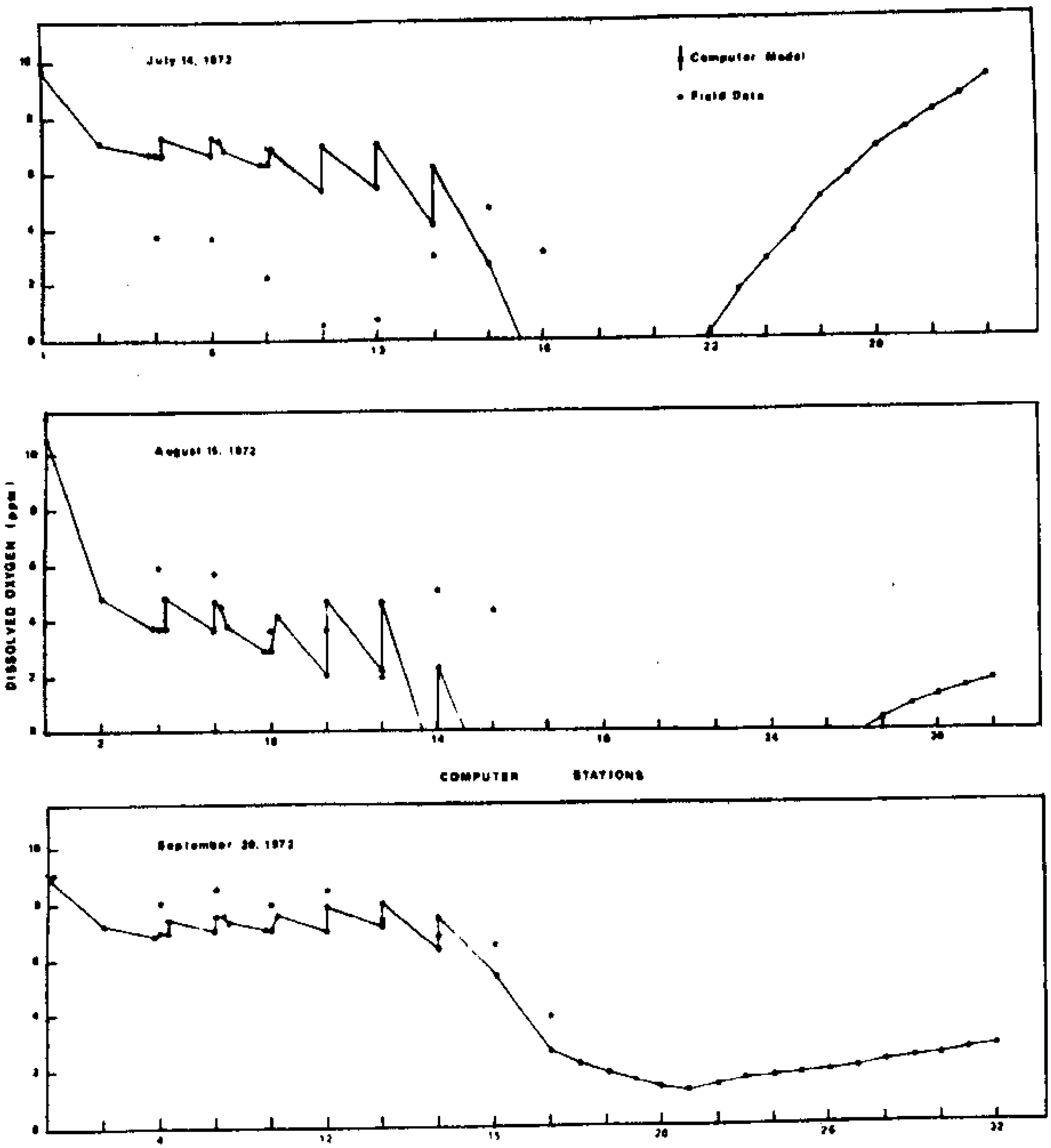

FIGURE 4 - VERIFICATION OF COMPUTER MODEL BY DISCRETE FIELD DATA VALUES

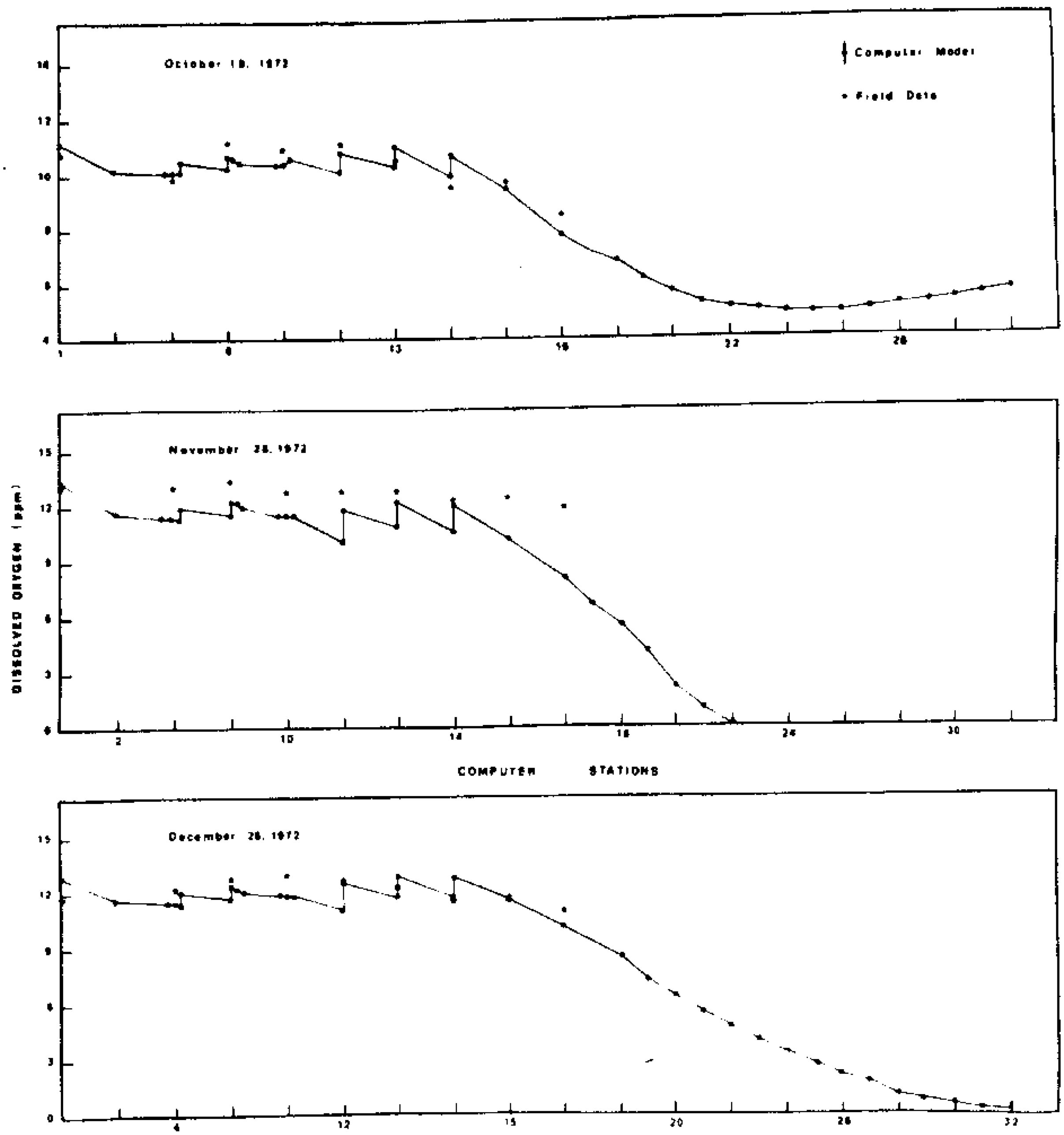

FIGURE 5 - VERIFICATION OF COMPUTER MODEL BY DISCRETE FIELD DATA VALUES

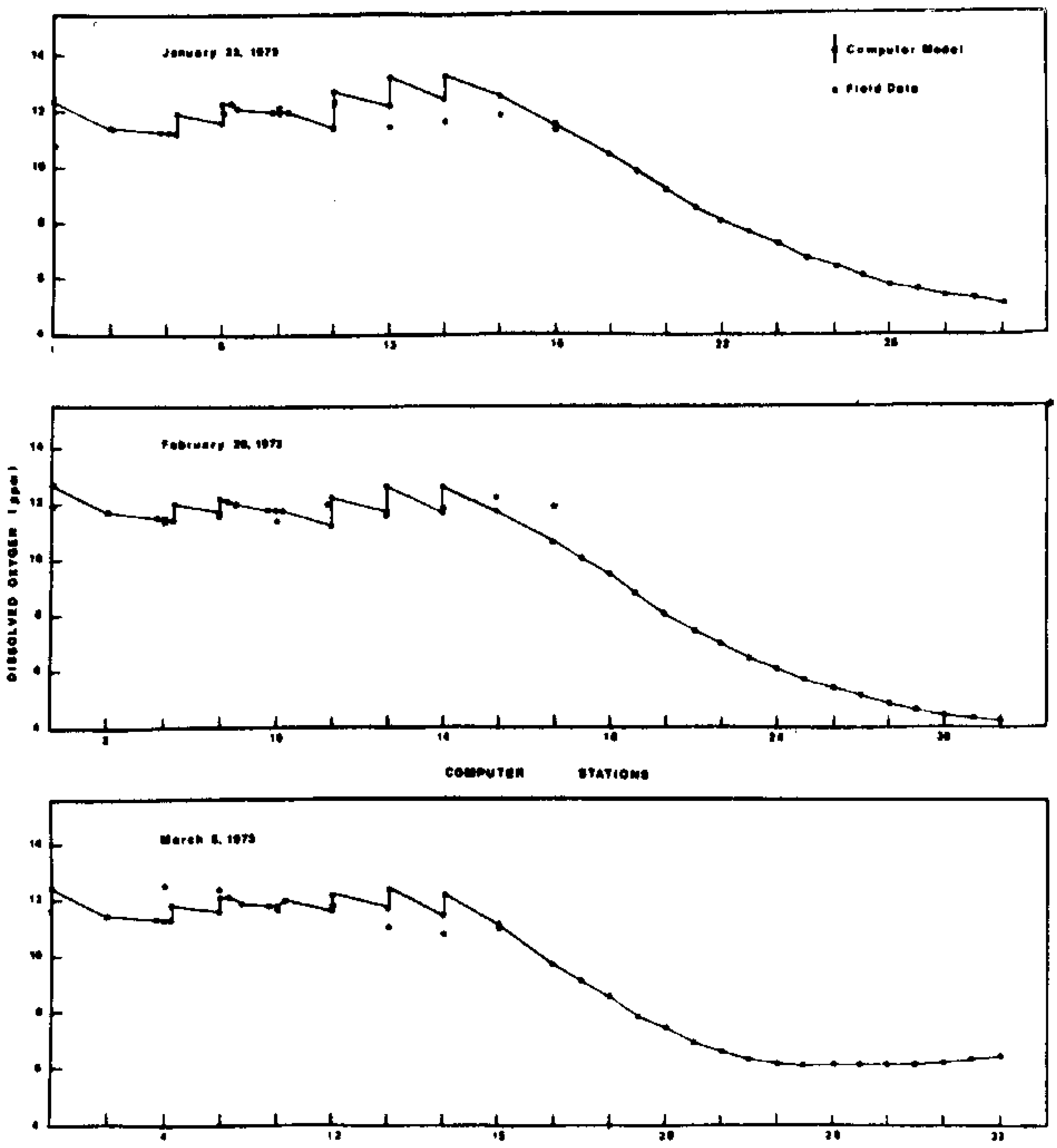

FIGURE 6 - VERIFICATION OF COMPUTER MODEL BY DISCRETE FIELD DATA VALUES

REFERENCES

1. FWPCA, U.S. Department of Interior, "A Comprehensive Water Pollution Control Program - Lake Michigan Basin - Green Bay Area," 1966.

2. P. E. Sager and J. W. Wiersma, Unpublished results presented at the technical conference "The Water Quality of the Lower Green Bay and Its Drainage Basin," Green Bay, Wisconsin, November 19, 1974.

3. Wisconsin DNR, Water Quality Evaluation Section, "Summary Report on Water Quality and Wastewater Discharges During the Summer of 1972," November, 1972, pp. 56-60.

4. Wisconsin DNR, Division of Resource Development, "Report on an Investigation of the Pollution in the Lower Fox River and Green Bay Made During 1966 and 1967," January 1968, pp. A1, A2.

5. D. Patterson, "Results of a Mathematical Water Quality Model of the Lower Fox River, Wisconsin," Wisconsin DNR, Bureau of Standards and Surveys, Water Quality Evaluation Section, March 1973, pp. 4,7.

6. L. Eder, "Development of a Computerized Mathematical System Model of the Lower Fox River from Lake Winnebago to Green Bay," Report to the Bureau of Water Resources, Division of Resource Development, Wisconsin DNR from Quirk, Lawler and Matusky, Engineering Consultants, 1969, pp. 14e, 18, 22.

7. D. Wentz, "The Importance and Behavior of Oxygen in Streams," Unpublished class notes for Advanced Water Chemistry, Course No. 240-770-8, University of Wisconsin, 1968, pp. 13, 20.

8. J. Wiersma, "Effects of Wisconsin Public Service Corporation's Pulliam Power Plant on Lower Green Bay," Report to Wisconsin Public Service Corporation, Green Bay, Wis., 1974, pp. 285-288.

APPENDIX I

This appendix contains a listing of the computer program used for teletypewriter operation.

```
C      LAN7
C      Q=FLØW RATE(CFS)
C      TEMP=TEMPERATURE ØF RIVER WATER(DEGREES CENT.).
C      DØA(1)=AMØUNT ØF DISSØLVED ØXYGEN ABØVE STATIØN 1.
C      TBS=TIME BETWEEN STATIØNS(DAYS)
C      TBIS=TIME BETWEEN INDUSTRY(PØLLUTER) AND NEXT STATIØN DØWNSTREAM
C      BØD=BØD PUT INTØ RIVERBY INDUSTRY(LBS./DAY)
C      PPM=BØD CØNVERTED TØ PPM
C      PPMC=TØTAL BØD ØXIDIZED
C      KN=RATE ØF NITRIFICATIØN(%)
C      TNIT=AMØUNT ØF NITRØGEN SAMPLED AT EACH STATIØN(PPM)
C      DØA=DISSØLVED ØXYGEN ABØVE A STATIØN(PPM)
C      DØB=AMØUNT ØF DISSØLVED ØXYGEN BELØW STATIØN(PPM)
C      DØID=DISSØLVED ØXYGEN INCREASE DUE TØ DAMS(PPM).
C      DØSAT=AMØUNT ØF DISSØLVED ØXYGEN IN SATURATED WATER(PPM)
C      PERSA=PERCENT SATURATIØN ØF WATER ABØVE DAM.
C      PERSB=PERCENT SATURATIØN ØF WATER BELØW DAM.
C      DØIC = SUM ØF DAM REAERATIØN
C      DØIA=DISSØLVED ØXYGEN INC. DUE TØ ATMØS. REAERATIØN
C       DØIS=SUM ØF DISSØLVED ØXYGEN INCREASE DUE TØ ATMØS. REA.
C      K2=ATMØSPHERIC REAERATIØN CØEFFICIENT
C      K2B=ATMØSPHERIC REAERATIØN CØEFFICIENT FØR THE DAY
C      RA=ALGAL RESPIRATIØN
C      RAC= CUMULATIVE RA
C      RSL= DØ DECREASE DUE TØ BØTTØM SLUDGE
C      RSLC= CUMULATIVE RSL
C      C=INDICATIØN ØF SECHI READING
C      DL= DAYLIGHT HØURS
C      PTC= CUMULATIVE PT
C      PM=MAXIMUM PHØTØSYNTHESIS RATE
C      KS=BØTTØM SLUDGE CØNSTANT
C      RR=MYSTERY TERM   CAN YØU FIND IT
C      PT= DØ INCREASE DUE TØ PHØTØSYNTHESIS
        INTEGER LP,CR
        REAL K2
        REAL K2B
        REAL KR
        REAL KN
        REAL MSAT
        REAL KS
        INTEGER XX
        INTEGER YY
        INTEGER RR
        DIMENSIØN BØD(34),PPM(34),TBIS(34),TBS(35),KN(35),PER(15),
       1RN(35),PPMC(35),TNIT(35),RNC(35),DØA(35),DØB(35),DØSAT(50),
       2PERSA(35),PERSB(35),DØID(35),TTBS(35),DØIA(35),
       3K2(15),H(35),W(15),RA(35),RAC(35),RH(15),RSL(15),PT(35),RR(26)
       4,ATBS(35),ATBIS(34),D1(12),D2(12),D3(12),D4(14),D5(16),D6(17),
       5D7(18),D8(20),D9(20),D10(20),D11(22),D12(23),D13(25),D14(30),
       6D15(34),P(32,34),DPS(32),A(64,32),T(64),RHS(64),CØST(64),
       7IFIX(22),TØL(5),
       8Y(65),S(100),CHL(16),PM(16),PA(32),C(16)
        DATA(T(J),J=1,64)/33*1H+,2*1H ,5*1H+,2*1H ,5*1H+,17*1H /
        CR=8
        LP=6
        N=34
        READ(CR,201)(BØD(J),J=2,N)
        READ(CR,202)(ATBS(J),J=1,33)
        READ(CR,203) ATBIS
        READ(CR,205)(PER(J),J=1,15)
        READ(CR,206) DØSAT
        READ(CR,207)(H(I),I=1,32)
        READ(CR,208) W
```

```
      READ(CR,209) RH
      READ(CR,210) KS
      READ(CR,215)(IPIX(J),J=1,22)
210   FORMAT(F10.3)
      KPB=.15
      RR(1)=1
      DO 4 K=2,26
      RR(K)=RR(K-1)+1
    4 CONTINUE
C     INITIALIZE A P(16,34) MATRIX TO BE 0.0 .
      DO 14 I=1,16
      DO 14 J=1,34
      P(I,J)=0.0
   14 CONTINUE
      DO 13 I=1,64
      DO 13 J=1,32
      A(I,J)=0.0
   13 CONTINUE
      RV=0.0
      DBIC=0.0
      STOS=0.0
      DOIS=0.0
      RAV=0.0
      RSLC=0.0
      PTC=0.0
      CR=5
      WRITE(LP,214)
214   FORMAT(/////,1X,'DO PROFILE PROGRAM',////)
      WRITE(LP,2210)
2210  FORMAT(' ENTER Q, DOA(1), TEMP, PPM(1), DL, AND MONTH (ONE VALUE P
     *ER LINE FOLLOWED BY A CARRIAGE RETURN).')
      READ(CR,211)Q
      READ(CR,211)DOA(1)
      READ(CR,211)TEMP
      READ(CR,211)PPM(1)
      READ(CR,211)DL
      READ(CR,211)MONTH
211   FORMAT(F10.2)
      WRITE(LP,212)
212   FORMAT(1X,'NOW ENTER THE AVERAGE OF 10 TNIT VALUES')
      READ(CR,211)TNIT(1)
      DO 213 J=2,16
      TNIT(J)=TNIT(1)
213   CONTINUE
      WRITE(LP,216)
216   FORMAT(1X,'NOW ENTER THE AVERAGE OF 10 CHL VALUES')
      READ(CR,211)CHL(1)
      DO 217 J=2,16
      CHL(J)=CHL(1)
217   CONTINUE
      WRITE(LP,220)
220   FORMAT(1X,'NOW ENTER THE AVERAGE OF 10 C(SECCHI) VALUES')
      READ(CR,211)C(1)
      C(1)=3.281*C(1)
      DO 221 J=2,16
      C(J)=C(1)
221   CONTINUE
      WRITE(LP,299)
299   FORMAT(1H1)
201   FORMAT(2X,13F6.0/2X,13F6.0/2X,7F6.0)
202   FORMAT(20F4.2/13F4.2)
203   FORMAT(16F5.3/16F5.3/2F5.3)
205   FORMAT(15F4.2)
206   FORMAT(20F4.1/2X,26F3.1/2X,4F3.1)
207   FORMAT(16F4.1/16F4.1)
208   FORMAT(15F5.0)
```

```
  209 FORMAT(13F6.2/2F6.2)
  215 FORMAT(15I5/2I5,A6,4I5)
      QT=TEMP-20.
      KR=.00014*Q*(1.05**QT)
      KS=KS*(1.06**QT)
      K2B=K2B*(1.02**QT)
       SPPM=PPM(1)
C     CHANGE CHLOROPHYLL A CONCENTRATION TO MAX PHOTOSYNTHETIC
C     PRODUCTION RATE (PM).
      DO 218 J=1,16
      PM(J)=.25*CHL(J)
      PA(J)=PM(J)*(1.02**QT)
  218 CONTINUE
C     CHANGE BOD FROM LBS./DAY TO PPM.
      DO 1 J=2,N
      PPM(J)=(BOD(J)*453000.)/(Q*3600.*24.*28.32)
      SPPM=SPPM+PPM(J)
    1 CONTINUE
C     CHANGE TIMES TO TIMES AS A FUNCTION OF RIVER FLOW(Q).
      DO 2 I=1,33
      TBS(I)=(ATBS(I)*1000.)/Q
    2 CONTINUE
      DO 3 I=1,34
      TBIS(I)=(ATBIS(I)*1000.)/Q
    3 CONTINUE
C     CALCULATE ATM REAERATION CONSTANT K2(M)
      DO 36 L=1,15
      K2(L)=(11.569*Q**.97)/(W(L)**.97*H(L)**2.64)
      K2(L)=K2(L)*(1.02**QT)
 36   CONTINUE
C     FIND MAXIMUM SATURATION(DISS. OX.) WATER CAN HOLD AT RIVER TEMP.
      IF(TEMP.GE.1.0) GO TO 35
      MSAT=14.6
      GO TO 38
   35 YY=TEMP
      MSAT=DOSAT(YY)
   38 DO 15 M=1,32
      IF(M.GT.15) GO TO 151
      SV=0.0
C     CALCULATE ALGAL RESPIRATION
      RA(M)=.1*PA(M)*TBS(M)
      RAV=RAV+RA(M)
      RAC(M)=RAV
C     CALCULATE RSL
      RSL(M)=(3.29*KS*TBS(M))/H(M)
      RSLC=RSLC+RSL(M)
C     COMPUTE PT
      PQ=(PA(M)*C(M))/(2.0*H(M))
      PT(M)=(DL/6.)*PQ*TBS(M)
      PTC=PTC+PT(M)
C     45 IS FOR A FULL DAM CALCULATION,54 IS FOR A HALF DAM ,AND 51 IS
C     WHERE THERE IS NO DAM.
      GO TO (45,51,51,51,54,54,51,51,51,51,51,45,45,45,51),M
   45 IF(DOA(M).LE.0.0) GO TO 53
C     IF STATION IS A DAM,CALCULATE DOID.
      PERSA(M)=(DOA(M)/MSAT)*100.
      PERSB(M)=.61*(PERSA(M))+39.
      DOB(M)=(PERSB(M)*MSAT)/100.
      DOID(M)=DOB(M)-DOA(M)
      DOIC=DOIC+DOID(M)
      GO TO 52
   53 DOID(M)=.39*MSAT
      DOB(M)=DOA(M)+DOID(M)
      DOIC=DOIC+DOID(M)
      GO TO 52
 54   IF(DOA(M).LE.0.0) GO TO 56
```

```
      PERSA(M)=(DBA(M)/MSAT)*100.
      PERSB(M)=.81*(PERSA(M))+19.5
      DBB(M)=(PERSB(M)*MSAT)/100.
      DBID(M)=DBB(M)-DBA(M)
      DBIC=DBIC+DBID(M)
      GO TO 52
 56   DBID(M)=.145*MSAT
      DBB(M)=DBA(M)+DBID(M)
      DBIC=DBIC+DBID(M)
      GO TO 52
C     IF STATION IS NOT A DAM,DBB=DBA.
   51 DBB(M)=DBA(M)
      DBID(M)=0.0
C     DO RN CALCULATION.
   52 IF(DBB(M).GE.0.5) GO TO 55
      KN(M)=0.0
      GO TO 65
   55 XX=(DBB(M)+.5)
      KN(M)=PER(XX)
 65   KN(M)=KN(M)*(1.02**BT)
      ZNIT=-.143*KN(M)*TBS(M)
      YNIT=EXP(ZNIT)
      RN(M)=(4.57*TNIT(M))*(1.0-YNIT)
      RNC(M)=RV+RN(M)
      RV=RNC(M)
C     DO PPMC CALCULATION
      GO TO (10,20,30,40,50,60,70,80,90,100,110,120,130,140,150),M
   10 L=12
      N=1
      GO TO 999
   20 L=12
      N=12
      GO TO 999
   30 L=12
      N=12
      GO TO 999
   40 L=14
      N=13
      GO TO 999
   50 L=16
      N=15
      GO TO 999
   60 L=17
      N=17
      GO TO 999
   70 L=18
      N=18
      GO TO 999
   80 L=20
      N=19
      GO TO 999
   90 L=20
      N=20
      GO TO 999
  100 L=20
      N=20
      GO TO 999
  110 L=22
      N=21
      GO TO 999
  120 L=23
      N=23
      GO TO 999
  130 L=25
      N=24
      GO TO 999
```

```
  140 L=30
      N=26
      GØ TØ 999
  150 L=34
      N=31
  999 DØ 1000 K=1,L
      IF(KR*THIS(K)-5.)75,71,71
 71   V=PPM(K)
      GØ TØ 77
 75   V=PPM(K)*(1.0-EXP(-KR*THIS(K)))
 77   SV=SV+V
C     DØ FRACTIØN ØXIDIZED CALCULATIØN.
      GØ TØ (19,29,39,49,59,69,79,89,99,109,119,129,139,149,159),M
   19 P(1,K)=V/PPM(K)
      GØ TØ 998
   29 P(2,K)=V/PPM(K)
      GØ TØ 998
   39 P(3,K)=V/PPM(K)
      GØ TØ 998
   49 P(4,K)=V/PPM(K)
      GØ TØ 998
   59 P(5,K)=V/PPM(K)
      GØ TØ 998
   69 P(6,K)=V/PPM(K)
      GØ TØ 998
   79 P(7,K)=V/PPM(K)
      GØ TØ 998
   89 P(8,K)=V/PPM(K)
      GØ TØ 998
   99 P(9,K)=V/PPM(K)
      GØ TØ 998
  109 P(10,K)=V/PPM(K)
      GØ TØ 998
  119 P(11,K)=V/PPM(K)
      GØ TØ 998
  129 P(12,K)=V/PPM(K)
      GØ TØ 998
  139 P(13,K)=V/PPM(K)
      GØ TØ 998
  149 P(14,K)=V/PPM(K)
      GØ TØ 998
  159 P(15,K)=V/PPM(K)
  998 THIS(K)=THIS(K)+THS(M+1)
 1000 CØNTINUE
      PPMC(M)=SV
C     SUM PPM IMPUTS FØR EACH SECTIØN ØF RIVER.
      GØ TØ (17,18,18,17,17,17,17,17,18,18,17,17,17,17,17),M
   18 DPS(M)=0.0
      GØ TØ 16
   17 SZ=0.0
      DØ 1002 J=N,L
      Z=PPM(J)
      SZ=SZ+Z
 1002 CØNTINUE
      DPS(M)=SZ
C     DØ PENALTY FACTØR CALCULATIØN.
   16 DØ 1001 J=N,L
      GØ TØ (219,229,2039,2049,2059,2069,2079,289,2099,3009,319,329,
     *339,349,359),M
  219 D1(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  229 D2(J)=0.0
      GØ TØ 1001
 2039 D3(J)=0.0
      GØ TØ 1001
 2049 D4(J)=PPM(J)/DPS(M)
```

```
      GØ TØ 1001
 2059 D5(J)=PPM(J)/DPS(M)
      GØ TØ 1001
 2069 D6(J)=PPM(J)/DPS(M)
      GØ TØ 1001
 2079 D7(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  289 D8(J)=PPM(J)/DPS(M)
      GØ TØ 1001
 2099 D9(J)=0.0
      GØ TØ 1001
 3009 D10(J)=0.0
      GØ TØ 1001
  319 D11(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  329 D12(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  339 D13(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  349 D14(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  359 D15(J)=PPM(J)/DPS(M)
 1001 CØNTINUE
C     DØ ATMØSPHERIC REAERATIØN CALCULATIØN
      IF(MØNTH .LT. 3  .ØR.  MØNTH .GT. 10) GØ TØ 27
      DØIA(M)=(MSAT-DØB(M))*(1.0-EXP(-K2(M)*TBS(M)))
      DØIS=DØIS+DØIA(M)
27    DØA(M+1)=DØA(1)+DØIS+DØIC+PTC-PPMC(M)-RNC(M)-RSLC-RAC(M)
      GØ TØ 15
C     EXTENSIØN ØF PRØGRAM INTØ BAY.
  151 TTBS(M)=STBS+TBS(M)
      STBS=TTBS(M)
      SV=0.0
      DPS(M)=0.0
C     CALCULATE ALGAL RESPIRATIØN
      RA(M)=.1*PA(16)*TBS(M)
      RAV=RAV+RA(M)
      RAC(M)=RAV
C     CØMPUTE PT
      PQ=(PA(16)*C(16))/(2.0*H(M))
      PT(M)=(DL/6.)*PQ*TBS(M)
      PTC=PTC+PT(M)
      DØB(M)=DØA(M)
      DØID(M)=0.0
      IF(DØB(M).GE.0.5) GØ TØ 155
      KN(M)=0.0
      GØ TØ 165
  155 XX=(DØB(M)+.5)
      KN(M)=PER(XX)
 165  KN(M)=KN(M)*(1.02**DT)
      ZNIT=-.143*KN(M)*TBS(M)
      YNIT=EXP(ZNIT)
      RN(M)=(4.57*TNIT(M))*(1.0-YNIT)
      RNC(M)=RNC(M-1)+RN(M)
      TNIT(M+1)=TNIT(M)-(RN(M)/4.57)
      DØ 9000 K=1,34
      IF(KR*TBIS(K)-5.)750,710,710
  710 V=PPM(K)
      GØ TØ 770
  750 V=PPM(K)*(1.0-EXP(-KR*TBIS(K)))
  770 SV=SV+V
C     DØ FRACTIØN ØXYDIZED CALCULATIØN FØR BAY.
      P(M,K)=V/PPM(K)
      TBIS(K)=TBIS(K)+TBS(M+1)
 9000 CØNTINUE
      PPMC(M)=SV
```

```
      IF(MØNTH .LT. 3  .ØR.  MØNTH .GT. 10) GØ TØ 28
      DØIA(M)=(MSAT-DØB(M))*(1.0-EXP(-K2B*THS(M)))
      DØIS=DØIS+DØIA(M)
28    DØA(M+1)=DØA(1)+DØIS+DØIC+PTC-PPMC(M)-RNC(M)-RSLC-RAC(M)
   15 CØNTINUE
C     DØ MINIMUM D.Ø. CALCULATIØN.
      DØ 556 M=1,32
      IF(M.GT.11) GØ TØ 554
C     UPPER RIVER CALCULATIØN (ABØVE WRIGHTSTØWN).
      RHS(M)=DØA(M+1)+PPMC(M)-5.0
      GØ TØ 556
  554 IF(M.GT.15) GØ TØ 555
C     LØWER RIVER CALCULATIØN (BELØW WRIGHTSTØWN TØ MØUTH).
      RHS(M)=DØA(M+1)+PPMC(M)-2.0
      GØ TØ 556
C     BAY CALCULATIØN.
  555 RHS(M)=DØA(M+1)+PPMC(M)-2.0
  556 CØNTINUE
      DØ 24 I=1,32
      DØ 24 J=1,32
      IF(I.GT.15) GØ TØ 3016
      GØ TØ (3001,3002,3003,3004,3005,3006,3007,3008,3109,3010,3011,3012
     *,3013,3014,3015),I
 3001 A(J,I)=D1(1)*P(J,1)+D1(2)*P(J,2)+D1(3)*P(J,3)+D1(4)*P(J,4)+D1(5)*
     1P(J,5)+D1(6)*P(J,6)+D1(7)*P(J,7)+D1(8)*P(J,8)+D1(9)*P(J,9)+D1(10)*
     2P(J,10)+D1(11)*P(J,11)+D1(12)*P(J,12)
      GØ TØ 24
 3002 A(J,I)=D2(12)*P(J,12)
      GØ TØ 24
 3003 A(J,I)=D3(12)*P(J,12)
      GØ TØ 24
 3004 A(J,I)=D4(13)*P(J,13)+D4(14)*P(J,14)
      GØ TØ 24
 3005 A(J,I)=D5(15)*P(J,15)+D5(16)*P(J,16)
      GØ TØ 24
 3006 A(J,I)=D6(17)*P(J,17)
      GØ TØ 24
 3007 A(J,I)=D7(18)*P(J,18)
      GØ TØ 24
 3008 A(J,I)=D8(19)*P(J,19)+D8(20)*P(J,20)
      GØ TØ 24
 3109 A(J,I)=D9(20)*P(J,20)
      GØ TØ 24
 3010 A(J,I)=D10(20)*P(J,20)
      GØ TØ 24
 3011 A(J,I)=D11(21)*P(J,21)+D11(22)*P(J,22)
      GØ TØ 24
 3012 A(J,I)=D12(23)*P(J,23)
      GØ TØ 24
 3013 A(J,I)=D13(24)*P(J,24)+D13(25)*P(J,25)
      GØ TØ 24
 3014 A(J,I)=D14(26)*P(J,26)+D14(27)*P(J,27)+D14(28)*P(J,28)+D14(29)*
     1P(J,29)+D14(30)*P(J,30)
      GØ TØ 24
 3015 A(J,I)=D15(31)*P(J,31)+D15(32)*P(J,32)+D15(33)*P(J,33)+D15(34)*
     1P(J,34)
      GØ TØ 24
C     EXTENSIØN ØF A MATRIX INTØ BAY.
 3016 A(J,I)=0.00
   24 CØNTINUE
      I=1
      DØ 25 J=33,64
      A(J,I)=1.0
      RHS(J)=DPS(I)
      I=I+1
   25 CØNTINUE
```

```
      DO 11 I=1,4
      TBL(I)=0.0
   11 CONTINUE
      TBL(5)=1000.
      DO 12 I=1,32
      COST(I)=-1.0
   12 CONTINUE
      WRITE(LP,240) DBIC
      WRITE(LP,241) DBIS
      WRITE(LP,247) RSLC
      WRITE(LP,249)PTC
      WRITE(LP,235)(DBA(I),I=1,33)
      WRITE(LP,237)(RR(I),I=1,10),(DBB(I),I=1,16),(RR(I),I=11,26),
     $ (DBB(I),I=17,32)
  240 FORMAT(5H DBIC/5X,F6.3)
  241 FORMAT(5H DBIS/5X,F6.3)
  247 FORMAT(5H RSLC/4X,F6.2)
  249 FORMAT(4H PTC/4X,F6.2)
  235 FORMAT(4H DBA/5X,11F8.3/5X,11F8.3/5X,11F8.3)
  237 FORMAT(4H DBB/4X,7HSTATION,2(4X,I2),2(10X,I2),[illegible]
     1I2)/11X,16F6.1//4X,7HSTATION,16(4X,I2)/11X,16F6.1)
      STOP
      END
```

APPENDIX II

This appendix contains a listing of the computer program used for the linear optimization of BOD inputs to the river.

```
FORTRAN-MACE 1.10C-02/14/7--00:27:57                    NAMES                    TO
C      LAST
C      Q=FLOW RATE(CFS)
C      TEMP=TEMPERATURE OF RIVER WATER(DEGREES CENT.).
C      DOA(1)=AMOUNT OF DISSOLVED OXYGEN ABOVE STATION 1.
C      TBS=TIME BETWEEN STATIONS(DAYS)
C      TBIS=TIME BETWEEN INDUSTRY(POLLUTER) AND NEXT STATION DOWNSTREAM
C      BOD=BOD PUT INTO RIVERBY INDUSTRY(LBS./DAY)
C      PPM=BOD CONVERTED TO PPM
C      PPMC=TOTAL BOD OXIDIZED
C      KN=RATE OF NITRIFICATION(()
C      TNIT=AMOUNT OF NITROGEN SAMPLED AT EACH STATION(PPM)
C      DOA=DISSOLVED OXYGEN ABOVE A STATION(PPM)
C      DOB=AMOUNT OF DISSOLVED OXYGEN BELOW STATION(PPM)
C      DOID=DISSOLVED OXYGEN INCREASE DUE TO DAMS(PPM).
C      DOSAT=AMOUNT OF DISSOLVED OXYGEN IN SATURATED WATER(PPM)
C      PERSA=PERCENT SATURATION OF WATER ABOVE DAM.
C      PERSB=PERCENT SATURATION OF WATER BELOW DAM.
C      DOIC = SUM OF DAM REAERATION
C      DOIA=DISSOLVED OXYGEN INC. DUE TO ATMOS. REAERATION
C      DOIS=SUM OF DISSOLVED OXYGEN INCREASE DUE TO ATMOS. REA.
C      K2=ATMOSPHERIC REAERATION COEFFICIENT
C      K2B=ATMOSPHERIC REAERATION COEFFICIENT FOR THE BAY
C      RA=ALGAL RESPIRATION
C      RAC= CUMULATIVE RA
C      RSL= DO DECREASE DUE TO BOTTOM SLUDGE
C      RSLC= CUMULATIVE RSL
C      C=INDICATION OF SECHI READING
C      DL= DAYLIGHT HOURS
C      PTC= CUMULATIVE PT
C      PM=MAXIMUM PHOTOSYNTHESIS RATE
C      KS=BOTTOM SLUDGE CONSTANT
C      KR=MYSTERY TERM   CAN YOU FIND IT
C      PT= DO INCREASE DUE TO PHOTOSYNTHESIS
       INTEGER LP,CR
       REAL K2
       REAL K2B
       REAL KR
       REAL KN
       REAL MSAT
       REAL KS
       INTEGER XX
       INTEGER YY
       INTEGER RR
       DOUBLE PRECISION X,PI,F,Y,RRJ
       DIMENSION BOD(34),PPM(34),TBIS(34),TBS(35),KN(35),PER(15),
      1RN(35),PPMC(35),TNIT(35),RNC(35),DOA(35),DOB(35),DOSAT(50),
      2PERSA(35),PERSB(35),DOID(35),TTBS(35),DOIA(35),
      3K2(15),H(35),W(15),RA(35),RAC(35),RH(15),RSL(15),PT(35),RR(26)
      4,ATBS(35),ATBIS(34),D1(12),D2(12),D3(12),D4(14),D5(16),D6(17),
      5D7(18),D8(20),D9(20),D10(20),D11(22),D12(23),D13(25),D14(30),
      6D15(34),P(32,34),DPS(32),A(64,32),T(64),RHS(64),COST(64),
      7IFIX(22),TOL(5),X(150),JX(65),PI(65),F(65,65),FRR(4),IOUT(4),
      8Y(65),S(130),CHL(16),PM(16),PA(32),C(16)
       DATA(T(J),J=1,64)/33*1H+,2*1H ,5*1H+,2*1H ,5*1H+,17*1H /
       CR=5
```

```
00120              LP=6
00121              N=34
00122              READ(CR,201)(ABD(J),J=2,N)
00130              READ(CR,202)(ATBS(J),J=1,33)
00136              READ(CR,203) ATBIC
00144              READ(CR,205)(PER(J),J=1,15)
00152              READ(CR,206) DOSAT
00160              READ(CR,207)(H(I),I=1,32)
00166              READ(CR,208) W
00174              READ(CR,209) RH
00202              READ(CR,210) KS
00205              READ(CR,215)(IFIX(J),J=1,27)
00213        210   FØRMAT(F10.3)
00214              K25=.15
00215              RR(1)=1
00216              DØ 4 K=2,26
00221              RR(K)=RR(K-1)+1
00222          4   CØNTINUE
00222        C     INITIALIZE A P(16,34) MATRIX TØ BE 0.0 .
00224              DØ 14 I=1,16
00227              DØ 14 J=1,34
00232              P(I,J)=0.0
00233           14 CØNTINUE
00236              DØ 13 I=1,64
00241              DØ 13 J=1,32
00244              A(I,J)=0.0
00245           13 CØNTINUE
00250              RV=0.0
00251              DØIC=0.0
00252              STBS=0.0
00253              DØIS=0.0
00254              RAV=0.0
00255              RSLC=0.0
00256              PTC=0.0
00257              CR=5
00260              WRITE(LP,214)
00262        214   FØRMAT(/////,1X,'DØ PRØFILE PRØGRAM',///)
00263              READ(CR,211)Q
00266              READ(CR,211)DØA(1)
00271              READ(CR,211)TEMP
00274              READ(CR,211)PPM(1)
00277              READ(CR,211)DL
00302              READ(CR,2111)MØNTH
00305        211   FØRMAT(F10.2)
00306         2111 FØRMAT(I2)
00307              READ(CR,211)TNIT(1)
00312              DØ 213 J=2,16
00315              TNIT(J)=TNIT(1)
00316        213   CØNTINUE
00320              READ(CR,211)CHL(1)
00323              DØ 217 J=2,16
00326              CHL(J)=CHL(1)
00327        217   CØNTINUE
00331              READ(CR,211)C(1)
00334              C(1)=3.281*C(1)
00335              DØ 221 J=2,16
00340              C(J)=C(1)
```

```
  221 CØNTINUE
      WRITE(LP,299)
  299 FØRMAT(1H1)
  201 FØRMAT(2X,13F6.0/2X,13F6.0/2X,7F6.0)
  202 FØRMAT(20F4.2/13F4.2)
  203 FØRMAT(16F5.3/16F5.3/2F5.3)
  205 FØRMAT(15F4.2)
  206 FØRMAT(20F4.1/2X,24F3.1/2X,4F3.1)
  207 FØRMAT(16F4.1/16F4.1)
  208 FØRMAT(15F5.0)
  209 FØRMAT(13F6.2/2F6.2)
  215 FØRMAT(15I5/2I5,A6,4I5)
      DT=TEMP-20.
      KS=.00014*Q*(1.05**DT)
      KG=KS*(1.06**DT)
      K28=K28*(1.02**DT)
       SPPM=PPM(1)
C     CHANGE CHLØRØPHYLL A CØNCENTRATIØN TØ MAX PHØTØSYNTHETIC
C     PRØDUCTIØN RATE (PM).
      DØ 218 J=1,16
      PM(J)=.25*CHL(J)
      PA(J)=PM(J)*(1.02**DT)
  218 CØNTINUE
C     CHANGE BØD FRØM LBS./DAY TØ PPM.
      DØ 1 J=2,N
      PPM(J)=(BØD(J)*453000.)/(Q*3600.*24.*28.32)
      SPPM=SPPM+PPM(J)
    1 CØNTINUE
C     CHANGE TIMES TØ TIMES AS A FUNCTIØN ØF RIVER FLØW(Q).
      DØ 2 I=1,33
      TBS(I)=(ATBS(I)*1000.)/Q
    2 CØNTINUE
      DØ 3 I=1,34
      TBIS(I)=(ATBIS(I)*1000.)/Q
    3 CØNTINUE
C     CALCULATE ATM REAERATIØN CØNSTANT K2(M)
      DØ 36 L=1,15
      K2(L)=(11.569*Q**.97)/(W(L)**.97*H(L)**2.44)
      K2(L)=K2(L)*(1.02**DT)
   36 CØNTINUE
C     FIND MAXIMUM SATURATIØN(DISS. ØX.) WATER CAN HØLD AT RIVER TEMP.
      IF(TEMP.GE.1.0) GØ TØ 35
      MSAT=14.6
      GØ TØ 38
   35 YY=TEMP
      MSAT=ØBSAT(YY)
   38 DØ 15 M=1,32
      IF(M.GT.15) GØ TØ 151
      SV=0.0
C     CALCULATE ALGAL RESPIRATIØN
      RA(M)=.1*PA(M)*TBS(M)
      RAV=RAV+RA(M)
      RAC(M)=RAV
C     CALCULATE RSL
      RSL(M)=(3.29*KS*TBS(M))/H(M)
      RSLC=RSLC+RSL(M)
C     CØMPUTE PT
```

```
00446             RQ=(PA(M)*C(M))/(2.0*H(M))
00447             PT(M)=(DL/6.)*RQ*TRS(M)
00450             PTC=PTC+PT(M)
00450       C     45 IS FOR A FULL DAM CALCULATION,54 IS FOR A HALF DAM ,AND 51 IS
00450       C     WHERE THERE IS NO DAM.
00451             GO TO (45,51,51,51,54,54,51,51,51,51,51,45,45,45,51),M
00452          45 IF(DBA(M).LE.0.0) GO TO 53
00452       C     IF STATION IS A DAM,CALCULATE DOID.
00454             PERSA(M)=(DBA(M)/MSAT)*100.
00455             PERSB(M)=.61*(PERSA(M))+39.
00456             DOB(M)=(PERSB(M)*MSAT)/100.
00457             DOID(M)=DOB(M)-DOA(M)
00460             DOIC=DOIC+DOID(M)
00461             GO TO 52
00462          53 DOID(M)=.39*MSAT
00463             DOB(M)=DBA(M)+DOID(M)
00464             DOIC=DOIC+DOID(M)
00465             GO TO 52
00466          54 IF(DBA(M).LE.0.0) GO TO 56
00470             PERSA(M)=(DBA(M)/MSAT)*100.
00471             PERSB(M)=.81*(PERSA(M))+19.5
00472             DOB(M)=(PERSB(M)*MSAT)/100.
00473             DOID(M)=DOB(M)-DOA(M)
00474             DOIC=DOIC+DOID(M)
00475             GO TO 52
00476          56 DOID(M)=.195*MSAT
00477             DOB(M)=DBA(M)+DOID(M)
00500             DOIC=DOIC+DOID(M)
00501             GO TO 52
00501       C     IF STATION IS NOT A DAM,DOB=DBA.
00502          51 DOB(M)=DBA(M)
00503             DOID(M)=0.0
00503       C     DO RN CALCULATION.
00504          52 IF(DOB(M).GE.0.5) GO TO 55
00506             KN(M)=0.0
00507             GO TO 65
00510          55 XX=(DOB(M)+.5)
00511             KN(M)=PER(XX)
00512          65 KN(M)=KN(M)*(1.02**ST)
00513             ZNIT=-.143*KN(M)*TRS(M)
00514             YNIT=EXP(ZNIT)
00515             RN(M)=(4.57*TNIT(M))*(1.0-YNIT)
00516             RNC(M)=RV+RN(M)
00517             RV=RNC(M)
00517       C     DO PPMC CALCULATION
00520             GO TO (10,20,30,40,50,60,70,80,90,100,110,120,130,140,150),M
00521          10 L=12
00522             N=1
00523             GO TO 999
00524          20 L=12
00525             N=12
00526             GO TO 999
00527          30 L=12
00530             N=12
00531             GO TO 999
00532          40 L=14
00533             N=13
```

```
      GØ TØ 999
   50 L=16
      N=15
      GØ TØ 999
   60 L=17
      N=17
      GØ TØ 999
   70 L=18
      N=18
      GØ TØ 999
   80 L=20
      N=19
      GØ TØ 999
   90 L=20
      N=20
      GØ TØ 999
  100 L=20
      N=20
      GØ TØ 999
  110 L=22
      N=21
      GØ TØ 999
  120 L=23
      N=23
      GØ TØ 999
  130 L=25
      N=24
      GØ TØ 999
  140 L=30
      N=26
      GØ TØ 999
  150 L=34
      N=31
  999 DØ 1000 K=1,L
      IF(KR*TBIS(K)-5.)75,71,71
   71 V=PPM(K)
      GØ TØ 77
   75 V=PPM(K)*(1.0-EXP(-KR*TBIS(K)))
   77 SV=SV+V
C     DØ FRACTIØN ØXIDIZED CALCULATIØN.
      GØ TØ (19,29,39,49,59,69,79,89,99,109,119,129,139,149,159),M
   19 P(1,K)=V/PPM(K)
      GØ TØ 998
   29 P(2,K)=V/PPM(K)
      GØ TØ 998
   39 P(3,K)=V/PPM(K)
      GØ TØ 998
   49 P(4,K)=V/PPM(K)
      GØ TØ 998
   59 P(5,K)=V/PPM(K)
      GØ TØ 998
   69 P(6,K)=V/PPM(K)
      GØ TØ 998
   79 P(7,K)=V/PPM(K)
      GØ TØ 998
   89 P(8,K)=V/PPM(K)
      GØ TØ 998
```

```
   99 P(9,K)=V/PPM(K)
      GØ TØ 998
  109 P(10,K)=V/PPM(K)
      GØ TØ 998
  119 P(11,K)=V/PPM(K)
      GØ TØ 998
  129 P(12,K)=V/PPM(K)
      GØ TØ 998
  139 P(13,K)=V/PPM(K)
      GØ TØ 998
  149 P(14,K)=V/PPM(K)
      GØ TØ 998
  159 P(15,K)=V/PPM(K)
  998 TØIS(K)=TØIS(K)+TØS(M+1)
 1000 CØNTINUE
      PPMC(M)=SV
C     SUM PPM IMPUTS FØR EACH SECTIØN ØF RIVER.
      GØ TØ (17,18,18,17,17,17,17,17,18,18,17,17,17,17,17),M
   18 DPS(M)=0.0
      GØ TØ 16
   17 SZ=0.0
      DØ 1002 J=N,L
      Z=PPM(J)
      SZ=SZ+Z
 1002 CØNTINUE
      DPS(M)=SZ
C     DØ PENALTY FACTØR CALCULATIØN.
   16 DØ 1001 J=N,L
      GØ TØ (219,229,2039,2049,2059,2069,2079,289,2099,3009,319,329,
     *339,349,359),M
  219 D1(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  229 D2(J)=0.0
      GØ TØ 1001
 2039 D3(J)=0.0
      GØ TØ 1001
 2049 D4(J)=PPM(J)/DPS(M)
      GØ TØ 1001
 2059 D5(J)=PPM(J)/DPS(M)
      GØ TØ 1001
 2069 D6(J)=PPM(J)/DPS(M)
      GØ TØ 1001
 2079 D7(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  289 D8(J)=PPM(J)/DPS(M)
      GØ TØ 1001
 2099 D9(J)=0.0
      GØ TØ 1001
 3009 D10(J)=0.0
      GØ TØ 1001
  319 D11(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  329 D12(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  339 D13(J)=PPM(J)/DPS(M)
      GØ TØ 1001
  349 D14(J)=PPM(J)/DPS(M)
```

```
      GO TO 1001
  369 D1S(J)=PPM(J)/DPS(M)
 1001 CONTINUE
C     DO ATMOSPHERIC REAERATION CALCULATION
      IF(MONTH .LT. 3  .OR.  MONTH .GT. 10) GO TO 27
      DOIA(M)=(MSAT-DOB(M))*(1.0-EXP(-K2(M)*TBS(M)))
      DOIS=DOIS+DOIA(M)
27    DOA(M+1)=DOA(1)+DOIS+DOIC+PTC-PPMC(M)-RNC(M)-RSLC-RAC(M)
      GO TO 15
C     EXTENSION OF PROGRAM INTO BAY.
  151 TTBS(M)=STBS+TBS(M)
      STBS=TTBS(M)
      SV=0.0
      DPS(M)=0.0
C     CALCULATE ALGAL RESPIRATION
      RA(M)=.1*PA(16)*TBS(M)
      RAV=RAV+RA(M)
      RAC(M)=RAV
C     COMPUTE PT
      PQ=(PA(16)*C(16))/(2.0*H(M))
      PT(M)=(DL/6.)*PQ*TBS(M)
      PTC=PTC+PT(M)
      DOB(M)=DOA(M)
      DOID(M)=0.0
      IF(DOB(M).GE.0.5) GO TO 155
      KN(M)=0.0
      GO TO 165
  155 XX=(DOB(M)+.5)
      KN(M)=PER(XX)
165   KN(M)=KN(M)*(1.02**QT)
      ZNIT=-.143*KN(M)*TBS(M)
      YNIT=EXP(ZNIT)
      RN(M)=(4.57*TNIT(M))*(1.0-YNIT)
      RNC(M)=RNC(M-1)+RN(M)
      TNIT(M+1)=TNIT(M)-(RN(M)/4.57)
      DO 3000 K=1,34
      IF(KR*TBIS(K)-5.)750,710,710
  710 V=PPM(K)
      GO TO 770
  750 V=PPM(K)*(1.0-EXP(-KR*TBIS(K)))
  770 SV=SV+V
C     DO FRACTION OXYDIZED CALCULATION FOR BAY.
      P(M,K)=V/PPM(K)
      TBIS(K)=TBIS(K)+TBS(M+1)
 3000 CONTINUE
      PPMC(1)=SV
      IF(MONTH .LT. 3  .OR.  MONTH .GT. 10) GO TO 28
      DOIA(M)=(MSAT-DOB(M))*(1.0-EXP(-K2B*TBS(M)))
      DOIS=DOIS+DOIA(M)
28    DOA(M+1)=DOA(1)+DOIS+DOIC+PTC-PPMC(M)-RNC(M)-RSLC-RAC(M)
   15 CONTINUE
C     DO MINIMUM D.O. CALCULATION.
      DO 556 M=1,32
      IF(M.GT.11) GO TO 554
C     UPPER RIVER CALCULATION (ABOVE WRIGHTSTOWN).
      RHS(M)=DBA(M+1)+PPMC(M)-5.0
      GO TO 556
```

```
01023        554 IF(M.GT.15) GØ TØ 555
01023  C         LØWER RIVER CALCULATIØN (BELØW WRIGHTSTØWN TØ MØUTH).
01025            RHS(M)=DØA(M+1)+PPMC(M)-2.0
01026            GØ TØ 556
01026  C         BAY CALCULATIØN.
01027        555 RHS(M)=DØA(M+1)+PPMC(M)-2.0
01030        556 CØNTINUE
01032            DØ 24 I=1,32
01035            DØ 24 J=1,32
01040            IF(I.GT.15) GØ TØ 3016
01042            GØ TØ (3001,3002,3003,3004,3005,3006,3007,3008,3109,3010,3011,3012
01042           *,3013,3014,3015),I
01043       3001 A(J,I)=D1(1)*P(J,1)+D1(2)*P(J,2)+D1(3)*P(J,3)+D1(4)*P(J,4)+D1(5)*
01043           1P(J,5)+D1(6)*P(J,6)+D1(7)*P(J,7)+D1(8)*P(J,8)+D1(9)*P(J,9)+D1(10)*
01043           2P(J,10)+D1(11)*P(J,11)+D1(12)*P(J,12)
01044            GØ TØ 24
01045       3002 A(J,I)=D2(12)*P(J,12)
01046            GØ TØ 24
01047       3003 A(J,I)=D3(12)*P(J,12)
01050            GØ TØ 24
01051       3004 A(J,I)=D4(13)*P(J,13)+D4(14)*P(J,14)
01052            GØ TØ 24
01053       3005 A(J,I)=D5(15)*P(J,15)+D5(16)*P(J,16)
01054            GØ TØ 24
01055       3006 A(J,I)=D6(17)*P(J,17)
01056            GØ TØ 24
01057       3007 A(J,I)=D7(18)*P(J,18)
01060            GØ TØ 24
01061       3008 A(J,I)=D8(19)*P(J,19)+D8(20)*P(J,20)
01062            GØ TØ 24
01063       3109 A(J,I)=D9(20)*P(J,20)
01064            GØ TØ 24
01065       3010 A(J,I)=D10(20)*P(J,20)
01066            GØ TØ 24
01067       3011 A(J,I)=D11(21)*P(J,21)+D11(22)*P(J,22)
01070            GØ TØ 24
01071       3012 A(J,I)=D12(23)*P(J,23)
01072            GØ TØ 24
01073       3013 A(J,I)=D13(24)*P(J,24)+D13(25)*P(J,25)
01074            GØ TØ 24
01075       3014 A(J,I)=D14(26)*P(J,26)+D14(27)*P(J,27)+D14(28)*P(J,28)+D14(29)*
01075           1P(J,29)+D14(30)*P(J,30)
01076            GØ TØ 24
01077       3015 A(J,I)=D15(31)*P(J,31)+D15(32)*P(J,32)+D15(33)*P(J,33)+D15(34)*
01077           1P(J,34)
01100            GØ TØ 24
01100  C         EXTENSIØN ØF A MATRIX INTØ BAY.
01101       3016 A(J,I)=0.00
01102         24 CØNTINUE
01105            I=1
01106            DØ 25 J=33,64
01111            A(J,I)=1.0
01112            RHS(J)=DFS(I)
01113            I=I+1
01114         25 CØNTINUE
01116            DØ 11 I=1,4
01121            TØL(I)=0.0
```

```
 11 CONTINUE
    TOL(5)=1000.
    DO 12 I=1,32
    COST(I)=-1.0
 12 CONTINUE
    WRITE(LP,240) DOIC
    WRITE(LP,241) DOIS
    WRITE(LP,247) RSLC
    WRITE(LP,249)PTC
    WRITE(LP,235)(DOA(I),I=1,33)
    WRITE(LP,237)(QR(I),I=1,10),(DOB(I),I=1,16),(QR(I),I=11,26),
   $ (DOB(I),I=17,32)
    WRITE(LP,266)(DPS(I),I=1,15)
    WRITE(LP,267)(D1(I),I=1,12)
    WRITE(LP,268)(D2(I),I=12,12)
    WRITE(LP,269)(D3(I),I=12,12)
    WRITE(LP,270)(D4(I),I=13,14)
    WRITE(LP,271)(D5(I),I=15,16)
    WRITE(LP,272)(D6(I),I=17,17)
    WRITE(LP,273)(D7(I),I=18,18)
    WRITE(LP,274)(D8(I),I=19,20)
    WRITE(LP,275)(D9(I),I=20,20)
    WRITE(LP,276)(D10(I),I=20,20)
    WRITE(LP,277)(D11(I),I=21,22)
    WRITE(LP,278)(D12(I),I=23,23)
    WRITE(LP,279)(D13(I),I=24,25)
    WRITE(LP,280)(D14(I),I=26,30)
    WRITE(LP,281)(D15(I),I=31,34)
    WRITE(LP,286)(IFIX(I),I=1,22)
    WRITE(LP,265)(RHS(I),I=1,64)
240  FORMAT(5H DOIC/5X,F6.3)
241  FORMAT(5H DOIS/5X,F6.3)
247  FORMAT(5H RSLC/4X,F6.2)
249  FORMAT(4H PTC/4X,F6.2)
235  FORMAT(4H DOA/5X,11F8.3/5X,11F8.3/5X,11F8.3)
237  FORMAT(4H DOB/4X,7HSTATION,2(4X,I2),2(10X,I2),22X,I2,10X,I2,4(4X,
    1I2)/11X,16F6.1//4X,7HSTATION,16(4X,I2)/11X,16F6.1)
 266 FORMAT(4H DPS/5X,8F8.3/5X,7F8.3)
 267 FORMAT(3H D1/5X,12F5.3)
 268 FORMAT(3H D2/5X,F5.3)
 269 FORMAT(3H D3/5X,F5.3)
 270 FORMAT(3H D4/5X,2F5.3)
 271 FORMAT(3H D5/5X,2F5.3)
 272 FORMAT(3H D6/5X,F5.3)
 273 FORMAT(3H D7/5X,F5.3)
 274 FORMAT(3H D8/5X,2F5.3)
 275 FORMAT(4H D9/5X,F5.3)
 276 FORMAT(4H D10/5X,F5.3)
 277 FORMAT(4H D11/5X,2F5.3)
 278 FORMAT(4H D12/5X,F5.3)
 279 FORMAT(4H D13/5X,2F5.3)
 280 FORMAT(4H D14/5X,5F5.3)
 281 FORMAT(4H D15/5X,4F5.3)
 286 FORMAT(17I6,A6,4I6)
 265 FORMAT(16F7.3/16F7.3/16F7.3/16F7.3)
     CALL DULPOX(A,T,RHS,COST,IFIX,TOL,OBJ,X,JX,PI,F,ERR,IOUT,Y,S)
     STOP
```

APPENDIX III

This appendix contains a listing of equation constants and the units used for each.

Parameter	Units
A	FT^2
C	METERS
C_p, C_s	ppm
DOSAT	ppm
H, H_A	FT
K_L	FT/DAY
KN_A	1/DAY
KR	1/DAY
KS	gm O_2/m^2 DAY
K_2, K2B	1/DAY
PA, PA_A	ppm/DAY
PER_A	%/DAY
PERSA, PERSB	ppm
PM	μg/ℓ
PPM_k	ppm
PQ	ppm/DAY
PT, PT_A	ppm
Q	FT^3/SEC
RSL	ppm
$TBIS_k$	DAYS
TBS, TBS_A	DAYS
$TNIT_A$	ppm
U	FT/DAY
V, VOL	FT^3
W, W_A	FT