Streamflow and Water Quality Modeling of the Chowan River

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The work upon which this report is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Research and Technology, as authorized by the Water Research and Development Act of 1978 (P.L. 95-467).

Project B-074-VA
VPI-VWRRC-BULL 119
4.25C

A publication of
Virginia Water Resources Research Center
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24060
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ACKNOWLEDGMENTS

We appreciate the cooperation of the following agencies which provided hydrologic and water quality data: Virginia State Water Control Board, Richmond, Virginia; U.S. Geological Survey, District Office, Raleigh, North Carolina; and North Carolina Department of Natural and Economic Resources, Division of Environmental Management, Raleigh, North Carolina. The funds for developing and running the computer models were provided by the Research Division of Virginia Tech. We would like to acknowledge also the Civil Engineering Department, Virginia Tech, for supporting travel expenditures when the OWRT project funds were depleted.

Special acknowledgment is made to the following individuals who generously gave their time to a critical review of the manuscript: David H. Howells, Water Resources Research Institute, North Carolina State University, Raleigh, North Carolina; and G. K. Young, GKY & Associates, Inc., Alexandria, Virginia. Acknowledgment is made also to Nancy L. Chapman for editorial processing and typesetting and to Gretchen S. Bingman for layout composition.
ABSTRACT

The Chowan River system in Southeast Virginia consists of three rivers that form two confluences before flowing into Albemarle Sound in North Carolina. This study investigated, by means of numerical simulation, the river's water quality problems related to excessive algal growth. A computer program was developed to determine flow rates, velocities, and depths at 51 computer stations by routing flows through the river system. The output of this flow program provided the input for calculating the concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), and four nitrogen parameters (organic, ammonia, nitrite-nitrate, and algal) at each of the computer stations. The four nitrogen parameters were solved for simultaneously. Measured field data collected in 1974 were used to calibrate the model. The program was then used to simulate algal growth for 1974 and 1975 and was compared with measured data for verification of the program.

The program was also used to study management strategies for water quality control. The first such plan was to measure the effects of reducing the concentration of nutrients from overland runoff on algal concentrations at the mouth of the river. Another application of the program assumed the watershed to consist only of forests and nutrient runoff from the forests to be the river's only nonpoint source of pollution. This primeval condition resulted in roughly half the concentrations measured in 1974.

INTRODUCTION

The Chowan River system consists of three rivers in Southeast Virginia that combine to become the Chowan River, which flows into Albemarle Sound in North Carolina. The lower portion of the Chowan River is a freshwater estuary with considerable fishing and recreational activity. Since 1970, this stretch of the river has experienced such severe algal blooms that these activities have been hampered. These algal occurrences were brought to the attention of the North Carolina Department of Natural and Economic Resources, Division of Environmental Management in Raleigh, and the North Carolina Water Resources Research Institute. An extensive program was begun to study the nature, cause, and management of the algal blooms. To do this effectively, a team of investigators from Virginia and North Carolina were brought together to collect, measure, and analyze data on nutrient flow and algae from different parts of the river system and to develop a mathematical model to simulate these parameters. It was felt that the most reliable way to evaluate any proposed management scheme would be with the use of a calibrated and verified mathematical model.

The Chowan River watershed is presented in Figure 1. The model presented in this study extends from the upper reaches of the watershed down to Holiday Island. M. Amien and W. Galler of North Carolina State University are developing another model which extends from the Virginia-North Carolina state line to the U.S. 17 bridge at Albemarle Sound. The watershed has a total area of 4,885 square miles. The lower portion of the river is tide-affected (wind and lunar), and consequently there are no permanent U.S. Geological Survey (USGS) stream gages in this area. The permanent USGS stream gages in the watershed are indicated in Figure 1, and their watershed area is roughly 60 percent of the total watershed area. It is for this reason that a flow model was necessary, and is used to calculate the flow rates, velocities, and depths. These characteristics are then used as input to the water quality model.

The water quality model has been developed to calculate the concentration of several water quality parameters. The main parameter of interest in this study is algae. The model is required to calculate the growth and decay of algae in the river system in response to flow rate, water temperature, nutrient concentrations, and insolation. This is accomplished by modeling the nitrogen content of the algae (agal nitrogen). Thus, the nitrogen cycle that is modeled consists of four parameters that interact
with each other: organic nitrogen $N_1$, ammonia nitrogen $N_2$, nitrite-nitrate nitrogen $N_3$, and algal nitrogen $N_4$. Besides the nitrogen cycle, the other water quality parameters that are modeled are biochemical oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO). This list of parameters is deemed sufficient to gage the water quality of the Chowan River (additional parameters could be added later). Reliable management studies could be made with this model to determine the impact of different management strategies.
LITERATURE REVIEW

I. Flow Models

Considerable experience has been gained in the past decade in modeling unsteady, one-dimensional flows in rivers and estuaries [Strelkoff, 1970; Baltzer and Lai, 1968; Amein and Fang, 1969; Contractor and Wiggert, 1972]. Several techniques have been developed for such models—the method of characteristics [Amein, 1966], finite difference methods [Miller, 1971; Gunaratnam and Perkins, 1970] and finite element methods [Cooley and Moin, 1976]. Of these methods, the implicit finite difference scheme appears to be highly favored [Price, 1974] because of its stability and accuracy. This method has been applied to study a variety of flow situations—for example, modeling stage-discharge relationships [Fread, 1973a], flow over flood plains [Abbot, Rodenhuis, and Verwey, 1971; Fread, 1976], and surge flow in open channels [Chaudhry and Contractor, 1973].

The Chowan River flow model had to incorporate the following features: (1) capability of using a few numbers of nodes to represent a very extensive river system, (2) unequal distances between nodes, (3) large time intervals in computation, (4) varying cross-sections of the river at each node, (5) wind and lunar tide effects, (6) handling the two confluences without too many additional iterations, (7) and properly handling the occurrence of extensive flow in the flood plains in certain reaches of the river. These requirements called for the use of the implicit method of solution. The problem of a river with large tributaries has been taken into account by iterating between the main river and the tributary until a particular tolerance criterion has been met [Fread, 1973b]. In this study, the solution of the depths and the flow rates everywhere in the system is obtained by the solution of a single large matrix. Details of this procedure are presented in the next section.

II. Water Quality Models

The earliest water quality model [Streeter and Phelps, 1958] dealt with the concentration of BOD and DO in a river. Since then, other parameters that affect the DO in the river, such as nitrogenous oxygen demand (NBOD), were modeled [Manhattan College, 1971]. Further development of water quality modeling proceeded along the lines of modeling the nitrogen and algal cycles [Thomann, O’Connor, and DiToro, 1970; Tho-
mann, 1972; Hann and Young, 1972; Leendertse, 1970; Masch and Shankar, 1969; Orlob, Shubinski, and Feigner, 1967] and their effects on dissolved oxygen. The initial models were sequential in nature and reactions were assumed to be linear. The next stage of development led to models that were interactive (had one or more feedback loops). And finally, models were developed that utilized the Michaelis-Menten formula instead of linear reaction rates. Under certain situations, the Michaelis-Menten formulation can be shown to degenerate to the linear formulation. This happens whenever the concentration of the water quality parameter being dealt with is much greater than the value of the corresponding half-saturation constant. Thus, under certain circumstances, it is valid to use the linear assumption.
MODEL FORMULATION

The streams in the upper reaches of the watershed were represented in the computer programs as shown in Figure 2. The locations of the 51 computer stations and the USGS topographic map on which they can be located are listed in Table 1. The number of computer stations chosen to represent the system is a compromise. Fewer stations would not represent the system adequately and would be likely to cause numerical instability in the computations. A larger number of stations would result in increased cost of computations and also would be limited by computer storage capability and accurate solution of simultaneous equations.

I. Streamflow Model

The streamflow model consists of a finite difference solution of unsteady open channel flow equations of continuity and momentum. These two equations are given below:

\[ \frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q - \text{EVAP} \]  

(1)

\[ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) + g A \left( \frac{\partial y}{\partial x} - S_o + S_f \right) - C \frac{g}{\rho} y^2 T \cos \alpha = 0 \]  

(2)

These equations take into account any evaporation that may take place from the free surface and also any shear stress exerted by the wind on the water surface. The equations were written in finite difference form for a reach length of \( \Delta x \) and a time step \( \Delta t \), where \( \theta \) is a weighting factor. When \( \theta = 0 \), an explicit formulation results. When \( \theta = 0.5 \), the Crank-Nicholson formulation results and when \( \theta = 1.0 \), a fully explicit scheme can be used. Such a scheme is also very useful for obtaining a steady state solution from the unsteady equations. Thus, by solving the unsteady equations with \( \theta = 1.0 \) and \( \Delta t \) equal to a very large value, the steady state solution is obtained. By making \( \Delta t \) very large, the time-dependent terms approach zero, and by making \( \theta = 1.0 \), the equations become independent of the initial conditions.

The cross-sections of the river were assumed to consist of a rectangular main channel with rectangular flood plains on both sides. Thus, each cross-section was characterized by a main channel with \( TW1 \), a main channel depth \( D1 \), and a flood plain width \( TW2 \). The flow in the Chowan
River is influenced considerably by flood plains. The existence of flood plains in the Chowan River can be seen in Figure 3, which is a map of the Chowan River and its surroundings. When the water level is in the main channel, the equations can be applied directly and the flow rate $Q$ and the depth $y$ can be solved for. However, when the water depth exceeds the main channel depth and flows also occur in the flood plains, the total flow is divided into main channel flow and flood plain flow. The ratio of flow in the main channel to flow in the flood plains is the same as the ratio of the conveyance of the main channel to the conveyance of the flood plain. Except for this adjustment, the solution for flow with flood plains is the same as for flow in the main channel. The conveyance is defined as $\frac{1.49}{n} AR^{2/3}$.

The following boundary conditions have to be applied. The inflow hydrographs have to be specified at the heads of the Blackwater River ($I = 1$), the Nottoway River ($I = 12$), and the Meherrin River ($I = 30$). The stage of the water surface at Holiday Island ($I = 51$) must be specified. Finally, the continuity and energy equations have to be applied at each confluence.

First Confluence

$Q_{11} + Q_{26} = Q_{27}$

and $E'_{11} = E'_{26} = E'_{27}$

or $y_{11} = y_{26} = y_{27}$

Second Confluence

$Q_{29} + Q_{43} = Q_{44}$

and $E'_{29} = E'_{43} = E'_{44}$

or $y_{29} = y_{43} = y_{44}$

The finite difference equations for each reach of the river system and the boundary conditions form a set of 102 non-linear algebraic equations. These equations have non-zero values in a narrow band about the main diagonal of the matrix, except for the equations describing the two confluences. Thus, the narrow bandwidth had to be widened to include the elements for the confluences. These wide bandwidth equations are solved by the Newton-Raphson technique. The solution algorithm used to solve the wide bandwidth equations is called Gauss Elimination Banded (GELB) and is part of the IBM Scientific Subroutine Package.

II. Water Quality Model

The water quality parameters that were of interest in this study included organic nitrogen $N_1$, ammonia nitrogen $N_2$, nitrite-nitrate nitrogen $N_3$, algal nitrogen $N_4$, COD, BOD, and DO. It was determined early in the
study [Stanley and Hobbie, 1977] that the growth of algae was nitrogen-limited in the Chowan River. Thus, phosphorus was not modeled because it did not play a role in limiting algal growth. The four nitrogen parameters interact with each other in the manner shown in Figure 4. The conversion of ammonia nitrogen N\(_2\) into nitrite-nitrogen and finally to nitrate-nitrogen is an oxygen-consuming reaction, and the nitrogen cycle is linked sequentially to the dissolved oxygen balance in this manner.

The mass balance equations for the water quality parameters are given below. These equations take into account convective transport, diffusive transport, chemical reactions, and lateral inflow of point sources and non-point sources.

The mass balance equations for the nitrogen cycle are:

\[
\frac{1}{A} \frac{\partial (N_1 A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial N_1}{\partial x} + EA \right) \right] = \frac{1}{A} \frac{\partial (N_2 A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial N_2}{\partial x} + EA \right) \right] = \frac{1}{A} \frac{\partial (N_3 A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial N_3}{\partial x} + EA \right) \right] = \frac{1}{A} \frac{\partial (N_4 A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial N_4}{\partial x} + EA \right) \right]
\]

\[
\frac{1}{A} \frac{\partial (N_2 A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial N_2}{\partial x} + EA \right) \right] = \frac{1}{2} \left( \frac{2}{A} + \frac{w_2}{dA} \right)
\]

\[
\frac{1}{A} \frac{\partial (N_3 A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial N_3}{\partial x} + EA \right) \right] = \frac{1}{2} \left( \frac{3}{A} + \frac{w_3}{dA} \right)
\]

\[
\frac{1}{A} \frac{\partial (N_4 A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial N_4}{\partial x} + EA \right) \right] = \frac{1}{2} \left( \frac{4}{A} + \frac{w_4}{dA} \right)
\]

The mass balance equation for COD is:

\[
\frac{1}{A} \frac{\partial (C A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial C}{\partial x} + EA \right) \right] = -K_C \frac{1}{A} + \frac{w_5}{dA}
\]

The mass balance equation for BOD is:

\[
\frac{1}{A} \frac{\partial (B A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial B}{\partial x} + EA \right) \right] = -K_B \frac{1}{A} + \frac{w_5}{dA}
\]

The mass balance equation for DOD (dissolved oxygen deficit) is:

\[
\frac{1}{A} \frac{\partial (D A)}{\partial t} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial D}{\partial x} + EA \right) \right] = -K_D \frac{1}{A} + K_C + \frac{w_5}{dA} + \frac{w_7}{dA}
\]
These equations were written in the implicit finite difference form for a
reach length $\Delta x$ and for a time interval $\theta (\Delta t)$, where $\theta$ is a weighting pa-
rameter similar to the one used in the streamflow model. By selecting
the appropriate value of $\theta$, different types of formulations can result. It
will be shown that the correct value of $\theta$ in the water quality equations
is 0.5. Steady state solutions to these equations can be obtained by mak-
ning $\theta = 1.0$ and $\Delta t$ equal to a very large number (approaching infinity).

Equations 3 through 9 must be solved in two different ways, depending
on the flow conditions at the end of the system (Holiday Island). When
the flow at Holiday Island is positive (leaving the system), no boundary
condition on any of the water quality parameters is required at Holiday
Island and the concentration there is determined by events occurring
within the system. On the other hand, when the flow at Holiday Island
is negative (entering the system), a boundary condition regarding the
concentration of the water quality parameter entering the system must
be specified. Thus, the number of boundary conditions and hence the
number of equations for the internal reaches differ with the flow condi-
tion at the end of the system. A simple example of a stream with 5 sta-
tions and 4 reaches will be used to illustrate the point. First, let the flow
at station 5 be positive. Five equations are required to solve for the 5
unknown concentrations of a water quality parameter at the 5 stations.
There will be one upstream boundary condition and an equation for each
of the 4 internal reaches, as shown below:

```
  I = 1  2  3  4  5

  Reach 1  Reach 2  Reach 3  Reach 4
```

When the flow at station 5 is negative, a boundary condition at 5 must
be used in addition to the upstream boundary condition. Thus, only 3
equations are available for the internal reaches. These reaches are spaced
about each internal station as shown below:

```
  I = 1  2  3  4  5

  Reach 1  Reach 2  Reach 3

  Boundary Conditions  Boundary condition
```
When solving equations 7, 8, or 9, 51 equations were to be solved for 51 unknowns. However, when solving equations 3 through 6, there were 4 unknowns at each computer station, resulting in 204 simultaneous equations to be solved.

The finite difference approximation of most of the terms in equations 3 through 9 are easy to write down since the variables are assumed to vary linearly between stations. However, the term containing the dispersion coefficient $E$ was written in finite difference form in the following manner:

\[
\frac{\partial}{\partial x} \left( EA \frac{\partial C}{\partial x} \right)_{I+1,J+1} = \frac{1}{\Delta x} \left[ \theta \left( EA \frac{\partial C}{\partial x} \right)_{I+1,J+1} - \left( EA \frac{\partial C}{\partial x} \right)_{I,J+1} \right] + (1 - \theta) \left[ \left( EA \frac{\partial C}{\partial x} \right)_{I+1,J} - \left( EA \frac{\partial C}{\partial x} \right)_{I,J} \right]
\]

where:

\[
\left( EA \frac{\partial C}{\partial x} \right)_{I+1,J+1} = E_{I+1,J+1} \cdot A_{I+1,J+1} \cdot \left( \beta_1 C_{I,J+1} + \beta_2 C_{I+1,J+1} + \beta_3 C_{I+2,J+1} \right)
\]

where $\beta_1$, $\beta_2$, $\beta_3$ are functions of $\Delta x_I$ and $\Delta x_{I+1}$, obtained by assuming a parabolic variation between $C_{I,J+1}$, $C_{I+1,J+1}$, and $C_{I+2,J+1}$. A similar expression can be used for $\left( EA \frac{\partial C}{\partial x} \right)_{I+1,J+1}$.

Also,

\[
\left( EA \frac{\partial C}{\partial x} \right)_{I,J+1} = E_{I,J+1} \cdot A_{I,J+1} \left( \beta_4 C_{I-1,J+1} + \beta_5 C_{I,J+1} \right) + \beta_6 C_{I+1,J+1}
\]
where $\beta_4$, $\beta_5$, $\beta_6$ are functions of $\Delta x_{i,j}$ and $\Delta x_{j,i}$, obtained by fitting a parabola through $C_{1,j+1}$, $C_{i,j+1}$, and $C_{i+2,j+1}$. A similar expression can be derived for the term $(AE \frac{\partial C}{\partial x})_{i,j}$.

For the upstream boundary condition, the concentration of the entering water quality parameter had to be known and specified. At each of the confluences, a mixing boundary condition of the type shown below had to be used.

Mixing condition at confluence:

$$Q_{11}C_{11} + Q_{26}C_{26} = Q_{27}C_{27}$$

However, conditions at the confluence are not always as shown above. Whenever negative flows occur at Holiday Island, it is possible that reverse flows occur at the confluences. When that happens, a non-mixing boundary condition of equal concentrations must be specified.

Non-mixing condition at confluence:

$$C_{27} = C_{26} = C_{11}$$

Thus, it can be seen that the flow conditions in the river system dictate the number and type of water quality equations to be solved. When the non-mixing boundary conditions were called for and used, the internal equations for the reaches were written for the nodal points, as explained previously for negative flows at the end of the river.

When the equations for the entire system are assembled, they appear as a banded matrix with most of the non-zero elements close to the main diagonal. However, the elements defining the two confluences make the band much wider. The same algorithm (GELB) is used to solve these equations as was used for the streamflow equations.
Two computer programs were written in Fortran IV—one for the streamflow model and the other for the water quality model. Both programs can be run using the WATFIV compiler. The two programs were not combined into a single program because it would have demanded an excessive storage requirement. Both programs can be run in either the steady state mode or the unsteady mode. The water quality program can be run for the nitrogen cycle, or for COD, BOD, or DOD, or any combination of the water quality parameters. Both the programs have print, or punch or plot options for the results. However, the plotter option may not be workable on other computers because of special statements applicable only to the computer at Virginia Tech. Some of the input data for the water quality program must come from the output of the flow program. This output is obtained in punched-card form from the flow model and consists of the discharge, cross-sectional area, flow depth, and the lateral inflow as a function of time for each of the computer stations. The water quality program provides for three options for the dispersion coefficient $E$. The value of $E$ can be set to zero, it can be calculated internally according to the Thackston equation, or it can be specified as a function of distance and time. The non-point sources can be specified in either of two ways: as a known concentration of overland runoff, or in lb/acre-year.
DATA INPUT

I. Streamflow Model

The input to the streamflow model consists of data describing the geometry of the stream, flow entering the river system, and environmental data. Data describing the geometry of the river system were the most difficult to obtain. These data include the elevations of the stream bed and the cross-sectional shape of the stream. The elevations of the stream bed were obtained from USGS topographic maps. However, when the stream bed was less than five feet above mean sea level, the elevation had to be obtained from the very little hydrographic data that were available. The cross-sectional shapes of the stream were actually measured in the lower reaches of the river [Daniel, 1977]. However, since no such measurements were available for the upper reaches of the Blackwater, Nottoway, and Meherrin rivers, engineering judgment was used to supply data whenever necessary. Because of this, the cross-sectional data—even though good enough for the purpose of this study—would not be adequate for the study of major floods.

The flow data to be used as input into the program consisted of flows from the following USGS gaging stations:

1. 2-0475 Blackwater River near Dendron, Virginia
2. 2-0440 Nottoway River near Burkeville, Virginia
3. 2-0510 North Meherrin River near Lunenburg, Virginia
4. 2-0460 Stony Creek near Dinwiddie, Virginia
5. 2-0516 Great Creek near Cochran, Virginia
6. 2-0525 Fontaine Creek near Brink, Virginia
7. 2-0532 Potecasi Creek near Union, North Carolina
8. 2-0535 Ahoskie Creek near Ahoskie, North Carolina

The Union Camp Paper Company releases water from its lagoons, and this flow, in addition to flows from the gaging stations, must also be input into the program. The stage of the water at Holiday Island must be known and input into the model. This parameter was measured by the USGS office in Raleigh, North Carolina, for the duration of this study and since has been discontinued. We recommend that the stage at Holiday Island be measured on a permanent basis so that the computer program could be used to calculate flows between Holiday Island and the permanent USGS gaging stations on the Blackwater, Nottoway,
and Meherrin rivers.

Finally, the environmental data required for the program consist of the wind velocity, wind direction, and the evaporation from a free-water surface. The wind velocity and evaporation could be obtained from a class-A weather station such as that at Holland, Virginia. The wind velocity and wind direction were measured for a short time during the life of the project.

II. Water Quality Model

The output of the streamflow model had to be part of the input to the water quality model. The particular flow parameters are the discharge or flow rate, the cross-sectional area of flow, the lateral inflow into each reach, and the depth of flow. These and all the other water quality parameters are to be input as a function of the computer station (i.e., distance) when the program is to be run in the steady state mode. When the program is to be run in the unsteady mode, all parameters have to be input as a function of time for each computer station. The temperature of the water and the wind velocity must be input following the flow data. Next, the breakdown of the watershed area into forested area, agricultural area, and urban area must be input as percentages for all computer stations. Most of these data for the Chowan River were compiled from Gannett et al. [1976]. The data are summarized in Table 2. Specific land use data for the lower reaches of the Chowan River were not available; thus, the land use data of the Meherrin were used for the Chowan.

The data for the non-point sources are entered next. These data can be input in either of two ways: (1) the concentration of the non-point sources may be specified—in this case, the variable BCONDS is set equal to unity; or (2) the loading rate from each land use category may be specified in lb/acre-year—in this case, the variable BCONDS is set equal to zero. Data on point sources were obtained from Tiyamani [1976] and state agencies concerned with water pollution and management. The point source data were divided into the effluent data from municipal sewage treatment plants (Table 3) and the major industrial point sources (Table 4).

The non-point source data also were obtained from state agencies. However, the quantity of non-point source data was very limited. Only a few of the tributary streams had water quality data available, and these data were of the grab sample type taken once or twice a month for a year or
so. The mean concentration of the water quality parameters of the gaged tributaries was obtained and used as input to the water quality model. The ungaged tributaries also brought in a non-point source contribution which was approximated by taking the mean concentration of all the gaged tributaries. These mean concentrations of $N_1$, $N_3$, BOD, and DOD are given in Table 5.

Table 5 also lists the rate constants at 20°C used in the model and temperature constants $\theta_1$ for correcting the rate constants for different temperatures. The first three rate constants $K_{12}$, $K_{11}$, and $K_{41}$ were obtained from the technical literature and therefore are subject to further scrutiny. The rate constant $K_{23}$ was measured in the laboratory and reported in Spangler [1975] and Miller [1975]. The rate constants $K_{24}$ and $K_{34}$ and the net photosynthesis $P_N$ were measured and reported in Stanley [1977]. A range of these values is indicated because the rate is a function of time—high in the summer months and low in the winter months. The monthly variation of these rates (presented in Figure 5) is due to the increased insolation that is available in the summer months. The BOD decay rate $K_1$ was measured and reported in Amein and Galler [1978]. The benthic oxygen demand rate $K_{BEN}$ was measured in situ by a team of scientists from the Environmental Protection Agency. The reaeration rate $K_2$ was calculated from the O’Connor formula with a correction for reaeration due to surface wind velocities [Mattingly, 1977].

Thus:

$$K_2 = 12.9 \frac{v^{0.5}}{y^{1.5}} \left( 1 + .0639 \frac{v^{1.643}}{a} \right).$$
MODEL CALIBRATION

I. Streamflow Model

In most streamflow models that have adequate data on stream geometry, the only parameter that has to be adjusted during calibration of the model is Manning's roughness coefficient \( n \). However, in this case, since adequate data on river cross-sections were not available, the parameters describing the cross-section at many stations also needed adjustment. The three parameters needed to define the cross-section are the bottom width of the main channel \( TW1 \), the depth of the main channel \( D \), and the width of the flood plain \( TW2 \). In many locations, the flood plains were narrow and did not affect the shape of the hydrograph passing through the cross-section. However, in some locations in the Nottoway and Meherrin rivers, the flood plains were very wide and did change the shape of the hydrograph passing through the sections. In the Nottoway, the flood plains are so extensive that the peak of the flood is delayed by four or five days.

Several attempts were made to vary the cross-section parameters in a systematic manner to bring the observed and computed hydrographs to a better fit [see Seetharama Rao, Contractor, and Tiyamani, 1976a and 1976b; Tiyamani, 1977]. These attempts were only partially successful. Figure 6 shows a comparison of flows at Holiday Island during September 1974. The comparison is made with the output of a hydrologic flow model developed by USGS [Daniel, 1977]. One can observe that both programs show days in which the flow at Holiday Island is negative.

II. Water Quality Model

Before calibrating the water quality model, the model output was checked against analytical results for steady flow and unsteady conditions to determine the accuracy of the program. In Figure 7, a steady flow with a BOD concentration of 10 mg/l was allowed to enter at the head of the Nottoway River. The flow was assumed to be saturated with dissolved oxygen at the head. As the BOD decayed with distance downstream, the DOD increased to a maximum and then decreased. This curve is the familiar DO sag curve and the analytical results are the familiar Streeter-Phelps solutions. It is apparent that the numerical results are good for a river length of 150 miles. In Figure 8, the concentration of a conservative substance was varied at the head of the Blackwater River in a normal or Gaussian manner, and the numerical results were
compared with analytical results.

It can be seen that if the weighting factor \( \theta \) were unity (i.e., the formulation was fully implicit), some numerical dispersion would result in the output. However, when \( \theta = 0.5 \) (i.e., the Crank-Nicholson formulation is used), the results are entirely satisfactory. Consequently, all of the subsequent unsteady runs were made with \( \theta = 0.5 \).

The water quality model was calibrated using data collected in September 1974. The variation of the water quality parameters along the Chowan River from the Virginia-North Carolina line to Holiday Island was compared with measured data taken during that month. The program was run in the steady-state mode, using mean monthly flow and temperature. Figures 9-13 show the variation of \( N_1, N_3, N_4, \text{BOD}, \) and \( \text{DO} \), respectively. In each figure, the data collected at each station along the river are presented by a range of values between the maximum and minimum with the average indicated by an asterisk. The number of data points available at each station is also given. A fertilizer plant called Farmers Chemical Industries, Inc., is located between stations 47 and 48. The groundwater table around this plant is saturated with \( N_2 \) and \( N_3 \) nitrogen, and seepage occurs into the river. The quantity of seepage into the river is very difficult to assess, and preliminary investigations showed that about 500 pounds of nitrogen seeped into the river a day. One run of the computer model was made with this loading. Because of the uncertainty of the quantity of seepage, another run was made with a loading of 2,500 pounds of nitrogen a day in order to provide a sensitivity to the response of the system. The measured data of nitrite-nitrate nitrogen and algal biomass show significant increases in concentration downstream from the Farmers Chemical Industries plant. The agreement between the measured data and the computed values can at best be regarded as a state-of-the-art verification. It would have been desirable to have had more data to define adequately a monthly average. Clearly, more work needs to be done to obtain more reliable rate constants and input data.
MODEL VERIFICATION

The rate constants obtained from the calibration runs were used to verify the program. A series of computer runs was made to define the variation of the water quality parameters as a function of time of year at any given station. In this series of runs, the flows and temperature were held constant at the mean monthly values. The water quality parameters were allowed to vary with respect to time. To determine the proper computational time interval \( DT \) to use for the water quality program, a series of runs was made, varying \( DT \) from one to four days. Figure 14 illustrates that as \( DT \) was increased, the solution began to develop numerical overshoot and instability. A value of \( DT \) of one day gives entirely stable results. A value of \( DT \) of two days shows only a very nominal amount of overshoot and instability and hence was used in the program. The choice of two days instead of one day as the time interval also resulted in half the number of iterations for a month and hence half the computer time and cost.

Figures 15-20 show the results of the water quality model for March 1974 through February 1975. The first four of these figures show the variation of nitrite-nitrate nitrogen, algal wet biomass, BOD, and DO at Winton, North Carolina. The principal features of these figures include a decrease of nitrite-nitrate nitrogen and DO and an increase in algal biomass and BOD during the summer months. Once again, the comparisons between measured and computed results show that the program reproduces the general features of the water quality variations and the comparison can be improved with more work. Figures 19 and 20 show the variation of algal biomass at two other locations further downstream from Winton. The general trends of algal biomass over the year are reproduced and promote a degree of confidence in the program.

The previous series of runs was made with the flow and temperature held constant at the mean monthly values, while the water quality parameters varied with time. The same approximate results would have been obtained if steady state values of the water quality parameters were obtained. Figure 21 shows a comparison of the results to the same set of input parameters of steady state computations and unsteady water quality computations. As shown in Figure 14, the water quality parameter varies from its initial value and reaches the steady state value in, say, \( \Delta \) days. The time \((\Delta)\) required to reach steady state conditions is dependent on the discharge flowing through the system. If the discharge is high, the time
Δ is small and if the discharge is low, the time Δ is large. The time Δ is similar to the time of concentration for the system. In those months when the mean monthly discharge is large enough to make Δ less than or equal to 30 days, the steady state value of the water quality parameter will be entirely satisfactory. In those months when the mean monthly discharge is so small that Δ exceeds 30 days, then the steady state value will not be a good approximation of the value at the end of the month. Figure 21 illustrates that in most months the steady state values were reached before the end of the month. In July and October, the unsteady computations did not reach the steady state values.

Whenever feasible, the water quality model should be run in the steady state mode because the steady state results are obtained with a single solution of the matrix. The unsteady results require 15 solutions of the matrix with DT = 2 days to simulate a month. Because of this, steady state calculations of algal growth were performed for the year 1975, and the results of the runs are presented in Figures 22 and 23. To make a valid comparison between the observed and calculated results, the nature of the observed data should be explained. The algal data presented are a single measured value at the breakpoints shown, with straight lines joining them. It should be realized that a single observation cannot possibly give one a satisfactory representative value of the algae at a cross-section of the river at a given time. The variability of algal concentrations in the river as a function of time of day is indicated in Table 6, taken from Stanley and Hobbie [1977].

Despite this variability with respect to time of day and possibly a similar variability across the width of the stream, we felt that the discrepancy between the measured and the computed results required further investigation, especially during August 1975. Thus, a special run was made to simulate algal growth during that month. In this run, the flow model was run in unsteady mode, thus providing daily flows that varied during the month. Finally, the water quality model was run in unsteady mode with DT = 1 day. The results of this run are presented in Figures 24 and 25. The results shown by circles indicate how the algae would grow and die in the river. The average of this variation is close to the steady state values indicated in Figures 22 and 23. This unsteady run was made with all the rate constants and input data unchanged from the previous runs. Of these rate constants, two were obtained from the technical literature, raising some question about their applicability to the Chowan River. These two rate constants were the settling rate of organic nitrogen.
KN1N1 and the death rate of algae KN4N1. We decided to make another run by modifying these two constants to the values shown in Figures 24 and 25. With these changes, the algal concentrations look more like the observed data.
MODEL APPLICATIONS

The streamflow and water quality models can be applied in numerous ways to study management strategies for water quality control. These applications include the following:

1. The effect of locating a new industry or sewage treatment plant along the river system on algal growth in the lower reaches;

2. The study of any change in the effluent of an existing industry or sewage treatment plant, e.g., if Union Camp changed to year-round discharge of its effluent;

3. The effect of a sustained wind blowing up-river and causing negative flows at Holiday Island on the level of algal concentrations;

4. The effect of a major land use change within the watershed, e.g., increasing agricultural land or urbanization of the watershed; and

5. The effect of different storm patterns moving through the watershed.

Two examples of model applications will be discussed. The first application is the study of the effect of reducing the concentration of nutrients in overland flows. Some form of management, whether by education or ordinance, will be required to decrease the concentration of non-point sources. The question was asked hypothetically what the response of the algae would be if the nutrient concentrations were reduced to 75, 50, 25, and zero percent of the measured levels used in the computer program. The results for 1974 are shown in Figures 26 and 27. It can be seen that even if there were no non-point sources, the point sources would still cause a low level of algal growth in the summer months. Proportionate decreases in algal biomass occur when the nutrient levels are decreased. The same is true also for the BOD concentrations as shown in Figure 27.

Of course, it is impossible to think of a situation in which there are no non-point sources. Table 2 shows that agriculture occurs in 12-26 percent of the watershed area. The urban component of land use is negligi-
ble. It is possible to conceive of a time when there was minimal agriculture and the watershed was covered with forests. Such a primeval condition can be simulated by the program if the runoff of nutrients (lb/acre-year) from forests could be estimated. A survey of technical literature reveals a range of runoff values measured from forests [Bedient, 1975; Southerland, 1974]. From these data, the following annual runoff values were used to simulate the primeval condition:

\[
\begin{align*}
\text{organic nitrogen } N_1 &= 0.67 \text{ lb/acre-year} \\
\text{ammonia nitrogen } N_2 &= 0.10 \text{ lb/acre-year} \\
\text{nitrite + nitrite nitrogen } N_3 &= 0.23 \text{ lb/acre-year} \\
\text{total nitrogen} &= 1.00 \text{ lb/acre-year}
\end{align*}
\]

The annual runoff quantities were distributed from month to month in direct proportion to the monthly flow rates in 1974. This distribution of runoff loading is shown in Figure 28. The monthly loading was input into the computer program and the algal response at Holiday Island was obtained and compared with the computer results for the present conditions (Figure 29). It can be seen that the primeval conditions account for slightly more than half the monthly algal concentrations and considerably more than the case of zero non-point source contributions. The difference between the present and the primeval conditions could be attributed to the influence of agricultural land use. It appears certain that if land use changes in which agriculture is increased considerably occur in the future, the nutrient runoff and consequently the algal growth in the Chowan River will be intensified.
SUMMARY AND CONCLUSIONS

1. An implicit flow model for the Chowan River has been developed. This model is capable of taking wind and lunar tides into account. The data describing the geometry of the system are weak in certain areas and should be improved by additional cross-sectional data and bed-elevation data. For the purpose of this study, the data are adequate. The output of this model has to be input into the water quality model.

2. A water quality model has been developed to simulate the nitrogen cycle, with algae included as a part of the nitrogen cycle. A linear model for interactions was deemed accurate enough for the purpose of this study. In addition to the nitrogen cycle, the program also calculates the COD, BOD, and DO in the river.

3. Most of the input data and the rate constants have been obtained from field measurements and experiments. Only a minimum number of constants have been taken from the technical literature.

4. The water quality model was verified against analytic results in both steady state and unsteady conditions. The value of the weighting factor \( \theta \) that gave the best agreement between numerical and analytic results was 0.5.

5. The water quality model was applied in steady state mode to the conditions in the stream during September 1974. The agreement between the numerical and measured quantities reflects the status of current modeling of algal growth. Precise reproduction of measured concentrations is not possible, even though the general trends of the phenomenon are followed. The measured data indicate significant rises in the nitrite-nitrate and algal concentrations just downstream of the Farmers Chemical Industries plant \( (I = 47) \). An initial estimate of 500 pounds of nitrogen a day was input into the model. This quantity was clearly not able to match the measured concentrations. A second run with 2,500 pounds of nitrogen a day was made, and even though the measured data are still not matched, the sensitivity of the response could be obtained from the results. It was not considered worthwhile to increase the loading until an adequate match occurred because conditions at the plant have changed since 1974.

6. The model was verified for monthly variations of water quality pa-
rameters during 1974. In these runs, the flow rate and water tempera-
ture were held at their mean monthly values; however, the water quality
parameters were allowed to vary with time. Once again, the agreement
between computed and measured results could be described as state-of-
the-art verification. The major trends of the phenomenon are depicted
by the model. These include a drop in the concentration of nitrite-nitrate
and dissolved oxygen during the summer months, with a consequent rise
in algal and BOD concentrations. Algal growth in 1975 was also verified.
The measured data indicate a peak concentration at the end of August
1975. The steady state results of the model did not provide a good match;
thus, it was decided to run the program in unsteady mode for the month
of August 1975. In this run, the flow rate, water temperature, and water
quality parameters were all allowed to vary on a daily basis. *Figures 24
and 25* show how the algal concentrations vary during the month. An-
other run was made by changing the values of two rate constants that
were not measured but which were obtained from the technical litera-
ture. The modified run gave results that conformed better to the two
measured data points.

7. The model was applied to show how the algae would respond if the
nutrient concentrations from non-point sources were reduced to 75,
50, 25, and zero percent of their current measured values. *Figures 26
and 27* show the decrease in algal and BOD concentrations when these
conditions occur. If a standard for algal concentration were set, it would
be possible to determine how much the concentration of the non-point
sources would have to be reduced to meet that standard.

8. The final application of the model was made to a primeval condition
in which the entire watershed was assumed to be covered with forests,
and non-point source runoff occurred only from the forests. *Figure 29
shows that roughly half of the algal concentrations that occurred in 1974
could be explained away by the primeval condition. Thus, the present
level of agriculture in the watershed probably contributed to the rest.
This indicates that any significant increase in agricultural land use could
have serious consequences on algal concentrations in the river.
RECOMMENDATIONS

1. The model developed here could be used immediately to investigate some preliminary management plans. However, the model should be updated as needed and its input data improved as additional data become available. Model improvement may consist of including phosphorus uptake by algae as another water quality parameter to model. Or, it may be deemed necessary to model a particular species or class of algae individually since it is known that different species respond in different ways to the same stimuli. The model currently uses mean concentrations of nutrients from non-point sources. As more data from more tributaries become available, it may be possible to specify better the spatial distribution of concentrations and the temporal distribution (at least monthly or seasonal).

2. The flow model could be improved by surveying the cross-sections of the upper reaches of the Blackwater, Nottoway, and Meherrin rivers. The model with better cross-sectional and bed-elevation data could be used for flood frequency and flood warning studies. Also, it would not be too difficult to modify the program to study the influence of constructing a reservoir at any location in the river system. The water quality model also could be modified to take into account the influence of a reservoir on the water quality downstream of the reservoir.

3. The U.S. Geological Survey should be encouraged to maintain some permanent water-stage recorders at strategic points in the lower reaches of the Chowan River. These data are vital for the execution of their computer model [Daniel, 1977], as well as the flow models described in this report and in Amein and Galler [1978].

4. The state agencies should continue to monitor the water quality in the stream not only to check the performance of the model but also to determine if some new phenomenon begins to control the water quality in the stream. These phenomena may include the contribution of nutrients from the sediments on the bottom of the river, from the swamps in the watershed, and from polluted groundwater inflow into the river system.
REFERENCES


Hann, Roy W., Jr., and P. J. Young, 1972. Mathematical Models of Water Quality Parameters for Rivers and Estuaries. TR 45. Texas Water Resources Institute, Texas A&M University, College Station, Texas.


FIGURE 1
Distribution of Stream Gages in the Chowan River Basin
FIGURE 2
Computer Stations in the Upper Reaches of the Chowan River
FIGURE 4
Nitrogen Cycle

NON-LIVING
ORGANIC NITROGEN

SETTLING

AMMONIA NITROGEN

NITRITE -
NITRATE NITROGEN

ALGAL NITROGEN
FIGURE 5
Monthly Variation of Parameters Related to Algal Growth

(a) RATES OF AMMONIA UPTAKE BY ALGAE

(b) RATES OF NITRATE UPTAKE BY ALGAE

(c) OXYGEN PRODUCTION BY ALGAE
FIGURE 6
Comparison of Flow at Holiday Island During September 1974

STATION I = 51

△ COMPUTED (REF. 10)
● COMPUTED USING STREAMFLOW MODEL
FIGURE 7
Comparison of Model Output with Analytical Results. Steady State Flows

CONCENTRATION, MG./L.

DISTANCE IN MILES NOTTOWAY RIVER

ANALYTICAL

NUMERICAL
FIGURE 8
Comparison of Model Output with Analytical Results. Unsteady Flows

- ANALYTICAL
- NUMERICAL $\theta = 0.5$
- NUMERICAL $\theta = 1.0$

$\Delta T = 9.0$ HRS.

INFLOW AT HEAD OF RIVER $I = 1$

OUTFLOW AT END OF RIVER $I = 11$
FIGURE 9
Variation of Organic Nitrogen from the Virginia-North Carolina Line to Holiday Island (September 1974)
FIGURE 10
Variation of Nitrite-Nitrate Nitrogen from the Virginia-North Carolina Line to Holiday Island (September 1974)

COMPUTED
MEASURED AVERAGE

NO. OF DATA POINTS N

NITRITE - NITRATE N, MG./L.

LOADING FROM FERTILIZER PLANT
LBS - N / DAY

COMPUTER STATIONS
RIVER MILES
FIGURE 11
Variation of Algal Wet Biomass from the Virginia-North Carolina Line to Holiday Island (September 1974)
FIGURE 12

Variation of BOD from the Virginia-North Carolina Line to Holiday Island (September 1974)

COMPUTED
MEASURED

AVERAGE
N NUMBER OF DATA POINTS

RIVER MILES

100 80 60 40 20 0

COMPUTER STATIONS

52 48 44 40 36 32 28 24 20 0

0.0 2.0 4.0 6.0 8.0 10.0

BOD, MG/L

NUMBER OF DATA POINTS
Figure 13
Variation of Dissolved Oxygen from the Virginia-North Carolina Line to Holiday Island (September 1974)
FIGURE 14
Effect of Computational Time Interval (DT) on Algal Response

Algal Wet Biomass, mg/L

TIME IN DAYS

DT (DAYS)

0 2 3 4

STEADY STATE SOLUTION

0.8 0.4 0.2

0

TIME IN DAYS

45
FIGURE 15
Variation of NO$_2$-NO$_3$ Nitrogen at Winton, North Carolina

I = 46

COMPUTED

AVERAGE

MEASURED

NO$_2$-NO$_3$ NITROGEN, MG./L.

1974

1975

NO. OF DATA POINTS

M A M J J A S O N D J F M A
FIGURE 16
Variation of Algal Biomass at Winton, North Carolina

ALGAL WET BIOMASS, MG./L.

1974 1975

I = 46

- COMPUTED

- AVERAGE MEASURED

N NO. OF DATA POINTS

1974 1975

M A M J J A S O N D J F M A

0 5 10 15 20 25
FIGURE 17
Variation of BOD at Winton, North Carolina

I = 46

- COMPUTED
- AVERAGE MEASURED

N NO. OF DATA POINTS

BOD, MG/L.

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</table>
FIGURE 18
Variation of Dissolved Oxygen at Winton, North Carolina

Computed
AVERAGE
MEASURED
N NO. OF DATA POINTS

1 = 46

M A M J J A S O N D 1 9 7 4
M A M J J A S O N D 1 9 7 5

D I S S O L V E D O X Y G E N , M G / L.
FIGURE 19
Variation of Algal Biomass Just Downstream of Fertilizer Plant

Algal Wet Biomass, MG/L.

1974

1975

I = 48 COMPLETED
AVERAGE MEASURED
N NO. OF DATA POINTS

25 20 15 10 5 0
FIGURE 20
Variation of Algal Biomass at Holiday Island

I = 51

COMPUTED

AVERAGE MEASURED

N NO. OF DATA POINTS

ALGAL WET BIOMASS, MG./L.

1974 1975

M A M J J A S O N D J F M A
Comparison of Steady State and Unsteady Computations

FIGURE 21

I = 51

STEADY STATE
UNSTEADY COMPUTATIONS

BOD, Mg/l
FIGURE 22
Variation of Algal Wet Biomass at Winton, North Carolina

Variation of Algal Wet Biomass, MG/L, 1975

1 = 46

○ MEASURED
○○ COMPUTED

ALGAL WET BIOMASS, MG/L

1975

J F M A M J J A S O N D

0 4 8 12 16 20
Algal Variation at Winton Using Daily Flows and Temperatures

FIGURE 24

Algal Wet Biomass, mg/l

I = 46

Measured Normal Run

\( \{ \text{KIN} = 0.035 \text{ days}^{-1} \} \)

\( \{ \text{KNI} = 0.12 \text{ days}^{-1} \} \)

Modified Run

\( \{ \text{KIN} = 0 \text{ days}^{-1} \} \)

\( \{ \text{KNI} = 0.08 \text{ days}^{-1} \} \)

Run with Mean Monthly Flow and Temperature

AUGUST 1975

0 4 8 12 16 20 24 28 32

0 4 8 12 16 20 24 28 32

20 16 12 8 4

0 4 8 12 16 20
Algal Variation at Holiday Island Using Daily Flows and Temperatures

FIGURE 25

Algal WET Biomass, mg/L

AUGUST 1975

20 16 12 8 4 0

20 16 12 8 4 0

28 24 20 16 12 8 4 0

MEASURED
NORMAL RUN

KMNI = 0.035 DAYS\(^{-1}\)
KN4NI = 0.12 DAYS\(^{-1}\)

MODIFIED RUN

KMNI = 0.09 DAYS\(^{-1}\)
KN4NI = 0.12 DAYS\(^{-1}\)
FIGURE 26
Effect of Reducing Concentration of Overland Runoff

I = 51

- O 100% OF MEASURED RUNOFF CONCENTRATION
- △ 75%
- □ 50%
- ○ 25%
- ● 0%

ALGAL WET BIOMASS, MG./L.

1974 1975

M A M J J A S O N D J F M A
FIGURE 27
Effect of Reducing Concentration of Overland Runoff

I = 51

- - - 100% OF MEASURED RUNOFF CONCENTRATION
- - - 75%
- - - 50%
- - - 25%
- - - 0%

BOD, MG./L.

1974 1975
M 1 2 3 4 5 6 7 8 9 10 11 12
A 1 2 3 4 5 6 7 8 9 10 11 12
J 1 2 3 4 5 6 7 8 9 10 11 12
A 1 2 3 4 5 6 7 8 9 10 11 12
S 1 2 3 4 5 6 7 8 9 10 11 12
O 1 2 3 4 5 6 7 8 9 10 11 12
N 1 2 3 4 5 6 7 8 9 10 11 12
D 1 2 3 4 5 6 7 8 9 10 11 12
J 1 2 3 4 5 6 7 8 9 10 11 12
F 1 2 3 4 5 6 7 8 9 10 11 12
M 1 2 3 4 5 6 7 8 9 10 11 12
A 1 2 3 4 5 6 7 8 9 10 11 12
FIGURE 28
Nutrient Loadings Assumed for Primeval Conditions

- O ORGANIC NITROGEN
- □ AMMONIA NITROGEN
- ● NITRITE- NITRATE NITROGEN

MEAN ANNUAL RUNOFF

ORG. N = 0.67 LBS/(AC.-YR)
NO₂-NO₃ N = 0.23 LBS/(AC.-YR)
AMM. N = 0.10 LBS/(AC.-YR)
FIGURE 29
Watershed Response Under Primitive Conditions

l = 51

- O - O - MEASURED CONC. OF RUNOFF FROM PRESENT LANDUSE
- O - O - RESPONSE OF SYSTEM IF ENTIRE WATERSHED IS
FORESTED (PRIMITIVE) CONDITIONS
- O - O - EXISTING POINT SOURCES AND ZERO CONCENTRATION
OF OVERLAND FLOW RUNOFF

ALGAL WET BIOMASS, MG./L.

1974

1975
TABLES
### TABLE 1
Locations of Computer Stations in the Upper Reaches of the Chowan River

<table>
<thead>
<tr>
<th>Computer Station No.</th>
<th>Blackwater River</th>
<th>USGS Topo Map</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dendron</td>
<td>USGS 2-0475, near Dendron, Va.; Walls Bridge on state highway 617</td>
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<tr>
<td>2</td>
<td>Raynor</td>
<td>Crossing with state highway 621 near Johnson Corner</td>
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<tr>
<td>3</td>
<td>Zuni</td>
<td>USGS 2-0480, at Zuni, Va.; bridge on U.S. 460</td>
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<tr>
<td>4</td>
<td>Zuni</td>
<td>State highway 603 bridge</td>
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<tr>
<td>5</td>
<td>Sedley</td>
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<tr>
<td>6</td>
<td>Franklin</td>
<td>At Joyner's Bridge on Rt. 611 north of Franklin, Va.</td>
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<td>7</td>
<td>Franklin</td>
<td>Crossing of U.S. 258 and 58 near WYSP radio tower</td>
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<tr>
<td>8</td>
<td>Franklin</td>
<td>Rt. 189 bridge south of Franklin, Va.</td>
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<td>9</td>
<td>Riverdale</td>
<td>8 miles below Rt. 58 bridge, south of Franklin, Va.</td>
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<td>10</td>
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<td>13 miles below Rt. 58 bridge south of Franklin, Va.</td>
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<tr>
<td>11</td>
<td>Riverdale</td>
<td>Mouth of Blackwater at Va.-NC state line; OWAR station no. BL-1.</td>
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<table>
<thead>
<tr>
<th>Computer Station No.</th>
<th>Nottoway River</th>
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<th>Description</th>
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<tr>
<td>12</td>
<td>Stony Creek</td>
<td>USGS 2-0440 near Burkeville, Va.; bridge on state highway 723</td>
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<tr>
<td>13</td>
<td>Blackstone West</td>
<td>On trail to state route 604.</td>
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<td>14</td>
<td>Blackstone West</td>
<td>Rt. 40 bridge, southwest of Blackstone, Va.</td>
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<tr>
<td>15</td>
<td>Danieltown</td>
<td>Crossing with Kennedy Bridge on state route 46</td>
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<tr>
<td>16</td>
<td>Warfield</td>
<td>USGS 2-0445 near Rawlings, Va.; Harpers Bridge south of bridge on state highway 612</td>
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<td>17</td>
<td>McKenney</td>
<td>On Cutbank Bridge, state route 609</td>
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<td>18</td>
<td>Jarratt</td>
<td>Smith Bridge on state route 630</td>
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<td>19</td>
<td>Stony Creek</td>
<td>USGS 2-0455 near Stony Creek, Va.; on U.S. 301 bridge</td>
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<td>20</td>
<td>Sussex</td>
<td>Crossing with state route 637</td>
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<td>21</td>
<td>Littleton</td>
<td>Crossing with state route 40 near gravel pit</td>
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<td>Sebrell</td>
<td>Crossing with Peters Bridge on state route 631</td>
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<td>23</td>
<td>Sebrell</td>
<td>USGS 2-0470 near Sebrell, Va.; 100 feet upstream of bridge on state route 653</td>
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<td>24</td>
<td>Courtland</td>
<td>Near state route 674 and sandpit</td>
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<td>25</td>
<td>Riverdale</td>
<td>Crossing with state route 684</td>
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<td>26</td>
<td>Riverdale</td>
<td>Mouth of Nottoway at Va.-N.C. state line; OWAR station no. N-1</td>
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<tr>
<td>Computer Station No.</td>
<td>USGS Topo Map</td>
<td>Description</td>
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<tr>
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<td>---------------</td>
<td>----------------------------------------------------------------------------</td>
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<tr>
<td>Chopan River</td>
<td></td>
<td></td>
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<tr>
<td>27</td>
<td>Riverdale</td>
<td>Just downstream of confluence of Blackwater and Nottoway rivers</td>
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<tr>
<td>28</td>
<td>Riverdale</td>
<td>At Gatlington Landing; OWAR station no. C-1</td>
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<tr>
<td>29</td>
<td>Riverdale</td>
<td>100 yards upstream from mouth of Meherrin River; OWAR station no. C-2</td>
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<td>Meherrin River</td>
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<td></td>
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<tr>
<td>30</td>
<td>Lunenburg</td>
<td>USGS 2-0510 North Meherrin River near Lunenburg, Va., on bridge of state hwy. 40</td>
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<tr>
<td>31</td>
<td>Wightman</td>
<td>Near Wilburn and state route 657</td>
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<td>32</td>
<td>North View</td>
<td>Crossing of Saffolds Bridge on state route 635</td>
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<td>33</td>
<td>Forksville</td>
<td>Union Mill Bridge on route 138</td>
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<td>34</td>
<td>Alberta</td>
<td>Crossing of Gees Bridge</td>
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<td>35</td>
<td>White Plains</td>
<td>State route 644 bridge</td>
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<tr>
<td>36</td>
<td>Powellton</td>
<td>USGS 2-0515 near Lawrenceville, Va.; 50 feet upstream from Gholson</td>
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<tr>
<td>37</td>
<td>Ante</td>
<td>At crossing Brunswick &amp; Greenville Co. pipe line</td>
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<td>38</td>
<td>Emporia</td>
<td>USGS 2-0520, Emporia, Va., bridge</td>
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<tr>
<td>39</td>
<td>Adams Grove</td>
<td>1½ miles north of state route 730</td>
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<tr>
<td>40</td>
<td>Margaretsville</td>
<td>Crossing with Hailey Bridge on state route 730</td>
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<td>41</td>
<td>Margaretsville</td>
<td>Route 195 bridge at Va.-N.C. state line</td>
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<tr>
<td>42</td>
<td>Winton</td>
<td>At U.S. 258 bridge in Murfreesboro, N.C.; OWAR station no. M-1</td>
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</tr>
<tr>
<td>43</td>
<td>Winton</td>
<td>Just upstream from mouth</td>
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</tr>
<tr>
<td>Chopan River</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>Winton</td>
<td>Just downstream from mouth of Meherrin</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Winton</td>
<td>At Gallows</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>Winton</td>
<td>At U.S. 13 bridge in Winton; OWAR station no. C-4</td>
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<td>At Seaboard Coastline railroad bridge</td>
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<td>48</td>
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<td>100 yards downstream from Farmers Chemical Fertilizer plant; OWAR station no. C-5</td>
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<td>49</td>
<td>Winton</td>
<td>At buoy 19; OWAR station no. C-6</td>
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<tr>
<td>50</td>
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<td>At buoy 13; OWAR station no. C-7</td>
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<td>51</td>
<td>Beckford</td>
<td>At Holiday Island; OWAR station no. C-8 and C-9</td>
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<td>River</td>
<td>% Forest</td>
<td>% Agriculture</td>
<td>% Urban</td>
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<td>14.6</td>
<td>0.5</td>
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<td>Location</td>
<td>Computer Station No.</td>
<td>Mean Daily Flow (mgpd)</td>
<td>Dissolved Oxygen (mg/I)</td>
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<tr>
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<td>mpd</td>
<td>cfs</td>
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<td>0.101</td>
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<tr>
<td>Jarratt</td>
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<td>0.06</td>
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<td>Total</td>
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(continued)
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<th>Location</th>
<th>Computer Station No.</th>
<th>Organic Nitrogen</th>
<th>NH\textsubscript{3}-N</th>
<th>NO\textsubscript{2} + NO\textsubscript{3}-N</th>
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<tr>
<td></td>
<td></td>
<td>mg/l</td>
<td>lbs/day</td>
<td>mg/l</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Waverly (inflow)</td>
<td>1</td>
<td>10.00</td>
<td>12.48</td>
<td>21.5</td>
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<td>4.18</td>
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<td>5.71</td>
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<td>23.0</td>
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<tr>
<td>Nottoway River</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Camp Pickett</td>
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<td>39.9</td>
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<td>2.66</td>
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<td>1.84</td>
<td>1.72</td>
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<td>8.1</td>
<td>4.66</td>
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<td>3.71</td>
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<td>15.7</td>
<td>21.0</td>
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<tr>
<td>Name of Industry</td>
<td>Computer Station No.</td>
<td>Mean Daily Flow</td>
<td>BOD</td>
<td>COD</td>
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<tr>
<td>---------------------------------------</td>
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<tr>
<td></td>
<td></td>
<td>mgd</td>
<td>cfs</td>
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<td>St. Regis Paper Co., Franklin, Va.</td>
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<td>Southern Johns-Manville Products Corp., Jarratt, Va.</td>
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<td>0.511</td>
<td>0.791</td>
<td>916</td>
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<td>Hercules, Inc., Delaware, Va.</td>
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<td>0.08</td>
<td>0.124</td>
<td>180</td>
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<td>H.P. Beale &amp; Sons, Beales, Va.</td>
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<td>0.055</td>
<td>0.0851</td>
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<td>Va. Dyeing Corp., Emporia, Va.</td>
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<td>1.216</td>
<td>1,897</td>
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TABLE 5
Summary of Input Data Used in the Study

Mean Concentration of Lateral (Tributary Flows)

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<th>Component</th>
<th>Concentration</th>
<th>Source</th>
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<tbody>
<tr>
<td>Organic nitrogen</td>
<td>0.35 mg/l</td>
<td>measured</td>
</tr>
<tr>
<td>Nitrite-nitrate nitrogen</td>
<td>0.211 mg/l</td>
<td>measured</td>
</tr>
<tr>
<td>BOD</td>
<td>1.90 mg/l</td>
<td>measured</td>
</tr>
<tr>
<td>Dissolved oxygen deficit (DOD)</td>
<td>1.74 mg/l</td>
<td>measured</td>
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</table>

Rate Constants at 20°C

<table>
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<tr>
<th>Reaction</th>
<th>Rate Constant</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion of organic nitrogen to ammonia nitrogen, $K_{12}$</td>
<td>0.05 days$^{-1}$</td>
<td>literature</td>
</tr>
<tr>
<td>Settling rate of organic nitrogen, $K_{11}$</td>
<td>0.035 days$^{-1}$</td>
<td>literature</td>
</tr>
<tr>
<td>Conversion of algal nitrogen to organic nitrogen, $K_{41}$</td>
<td>0.12 days$^{-1}$</td>
<td>literature</td>
</tr>
<tr>
<td>Conversion of ammonia nitrogen to $\text{NO}_2 + \text{NO}<em>3 \text{N}$, $K</em>{23}$</td>
<td>0.60 days$^{-1}$</td>
<td>measured</td>
</tr>
<tr>
<td>Ammonia nitrogen uptake by algae, $K_{24}$</td>
<td>0.1-1.0 days$^{-1}$</td>
<td>measured</td>
</tr>
<tr>
<td>$\text{NO}<em>3 \text{N}$ uptake by algae, $K</em>{34}$</td>
<td>0.01-0.15 days$^{-1}$</td>
<td>measured</td>
</tr>
<tr>
<td>BOD decay, $K_1$</td>
<td>0.16 days$^{-1}$</td>
<td>measured</td>
</tr>
<tr>
<td>Benthic oxygen demand, $K_{BEN}$</td>
<td>0.75 gm/(m$^2$·day)</td>
<td>measured</td>
</tr>
<tr>
<td>Net photosynthesis, $P_N$</td>
<td>0.1-2.5 gm/(m$^2$·day)</td>
<td>measured</td>
</tr>
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Temperature Constants, $\theta_1$ in $K_T = K_{20}^{\theta_1}$ (T-20)

<table>
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<tr>
<th>Reaction</th>
<th>$\theta_1$</th>
<th>Source</th>
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<td>literature</td>
</tr>
<tr>
<td>Conversion of ammonia nitrogen to $\text{NO}_2 = \text{NO}_3 \text{N}$</td>
<td>1.05</td>
<td>literature</td>
</tr>
<tr>
<td>Conversion of ammonia nitrogen to algal nitrogen</td>
<td>1.127</td>
<td>measured</td>
</tr>
<tr>
<td>Conversion of $\text{NO}_2 + \text{NO}_3 \text{N}$ to algal nitrogen</td>
<td>1.108</td>
<td>measured</td>
</tr>
<tr>
<td>Conversion of algal nitrogen to organic nitrogen</td>
<td>1.05</td>
<td>literature</td>
</tr>
<tr>
<td>BOD</td>
<td>1.047</td>
<td>literature</td>
</tr>
<tr>
<td>Benthic oxygen demand</td>
<td>1.065</td>
<td>literature</td>
</tr>
<tr>
<td>Photosynthesis</td>
<td>1.087</td>
<td>measured</td>
</tr>
<tr>
<td>Reaeration</td>
<td>1.024</td>
<td>literature</td>
</tr>
</tbody>
</table>

Average ratio of wet algal biomass to algal C = 10
Average ratio of algal carbon to algal nitrogen = 7
### TABLE 6
Variability of Algal Concentrations in the Chowan River as a Function of Time

<table>
<thead>
<tr>
<th>Date</th>
<th>Station</th>
<th>Time (hours)</th>
<th>Algal Wet Weight (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 31, 1975</td>
<td>Winton</td>
<td>0600</td>
<td>34.63</td>
</tr>
<tr>
<td>August 31, 1975</td>
<td>Winton</td>
<td>0800</td>
<td>5.98</td>
</tr>
<tr>
<td>August 31, 1975</td>
<td>Winton</td>
<td>1400</td>
<td>30.77</td>
</tr>
<tr>
<td>August 31, 1975</td>
<td>Winton</td>
<td>1600</td>
<td>26.86</td>
</tr>
<tr>
<td>August 31, 1975</td>
<td>Winton</td>
<td>1800</td>
<td>15.84</td>
</tr>
<tr>
<td>August 31, 1975</td>
<td>Winton</td>
<td>2000</td>
<td>9.46</td>
</tr>
<tr>
<td>August 31, 1975</td>
<td>Winton</td>
<td>2200</td>
<td>8.02</td>
</tr>
<tr>
<td>August 31, 1975</td>
<td>Winton</td>
<td>2400</td>
<td>13.56</td>
</tr>
<tr>
<td>September 1, 1975</td>
<td>Winton</td>
<td>0200</td>
<td>5.10</td>
</tr>
<tr>
<td>September 1, 1975</td>
<td>Winton</td>
<td>0400</td>
<td>10.34</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Cross-sectional area of flow in river</td>
<td>sq ft</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Biochemical oxygen demand (BOD)</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Chemical oxygen demand (COD)</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>C_a</td>
<td>Wind stress coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Dissolved oxygen deficit (DOD)</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>D_1</td>
<td>Depth of main channel</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>E'</td>
<td>Specific energy (= y + V^2/2g )</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Dispersion coefficient</td>
<td>ft²/sec</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
<td>ft/sec²</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Station designation in the (x) direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>Time counter in multiples of (\Delta t)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K_1</td>
<td>BOD decay rate constant</td>
<td>(days)^{-1}</td>
<td></td>
</tr>
<tr>
<td>K_2</td>
<td>Reaeration rate constant</td>
<td>(days)^{-1}</td>
<td></td>
</tr>
<tr>
<td>K_{BEN}</td>
<td>Benthic oxygen demand rate constant</td>
<td>gm/m²·day</td>
<td></td>
</tr>
<tr>
<td>K_c</td>
<td>COD decay rate constant</td>
<td>(days)^{-1}</td>
<td></td>
</tr>
<tr>
<td>K_{ii}</td>
<td>Settling rate of (N_i)</td>
<td>(days)^{-1}</td>
<td></td>
</tr>
<tr>
<td>K_{ij}</td>
<td>Rate constant of conversion from (N_i) to (N_j)</td>
<td>(days)^{-1}</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>Manning’s roughness coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N_1</td>
<td>Organic nitrogen concentration</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>N_2</td>
<td>Ammonia nitrogen concentration</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>N_3</td>
<td>Nitrite-nitrate nitrogen concentration</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>N_4</td>
<td>Algal nitrogen concentration</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>P_N</td>
<td>Net photosynthesis</td>
<td>gm/m²·day</td>
<td></td>
</tr>
<tr>
<td>q_L</td>
<td>Lateral inflow (cfs/unit stream length)</td>
<td>ft²/sec</td>
<td></td>
</tr>
<tr>
<td>q_{EVAP}</td>
<td>Evaporation rate</td>
<td>ft²/sec</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>Flow rate</td>
<td>ft³/sec</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>Hydraulic radius</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>S_o</td>
<td>Slope of stream bed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_f</td>
<td>Friction slope given by Manning’s equation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>sec</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Top width of water surface</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>T{\text{W1}}</td>
<td>Bottom width of main channel</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>T{\text{W2}}</td>
<td>Top width of flood plain</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Velocity of stream</td>
<td>ft/sec</td>
<td></td>
</tr>
<tr>
<td>V _</td>
<td>Volume flow rate of point source</td>
<td>ft³/sec</td>
<td></td>
</tr>
<tr>
<td>V_a</td>
<td>Wind velocity</td>
<td>ft/sec</td>
<td></td>
</tr>
<tr>
<td>w_j</td>
<td>Non-point source concentration</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>W_j</td>
<td>Point source concentration</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>Distance along stream</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>y</td>
<td>Stream depth</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Angle between wind and stream</td>
<td>lbs-s$^2$/ft$^2$</td>
<td></td>
</tr>
<tr>
<td>$\beta_1 \cdot \beta_6$</td>
<td>Functions of $\Delta x_{i,j}$, $\Delta x_j$, $\Delta x_{j+1}$</td>
<td>lbs-s$^2$/ft$^2$</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Mass density of water</td>
<td>lbs-s$^2$/ft$^2$</td>
<td></td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>Mass density of air</td>
<td>lbs-s$^2$/ft$^2$</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>Weighting factor</td>
<td>lbs-s$^2$/ft$^2$</td>
<td></td>
</tr>
<tr>
<td>$\theta_1$</td>
<td>Temperature constant for reaction rates</td>
<td>lbs-s$^2$/ft$^2$</td>
<td></td>
</tr>
</tbody>
</table>
The Virginia Water Resources Research Center is a federal-state partnership agency attempting to find solutions to the state's water resources problems through careful research and analysis. Established at Virginia Polytechnic Institute and State University under provisions of the Water Research and Development Act of 1978 (P.L. 95-467), the Center serves five primary functions:

- It studies the state's water and related land-use problems, including their ecological, political, economic, institutional, legal, and social implications.
- It sponsors and administers research investigations of these problems.
- It collects and disseminates information about water resources and water resources research.
- It provides training opportunities in research for future water scientists enrolled at the state's colleges and universities.
- It provides other public services to the state in a wide variety of forms.

More information on programs and activities may be obtained by contacting the Center at the address below.

Virginia Water Resources Research Center  
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Blacksburg, Virginia 24060  
Phone (703) 961-5624