PHOSPHORUS DYNAMICS BETWEEN JAMES RIVER AND CHESAPEAKE BAY

by

Chiu-Shia Fen

December 1988

SCHOOL OF ENGINEERING AND APPLIED SCIENCE

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA 22901

PHOSPHORUS DYNAMICS BETWEEN JAMES RIVER AND CHESAPEAKE BAY

A Thesis Presented to

the Faculty of the School of Engineering and Applied Science

University of Virginia

In Partial Fulfillment

of the requirement for the Degree

Master of Science in Civil Engineering

by

Chiu-Shia Fen

December 1988

ACKNOWLEDGEMENT

I wish to express my thanks to Dr. Wu-Seng Lung for his advice and guidance. His assistance was invaluable in the completion of this thesis. The Soap and Detergent Association is appreciated for providing financial support for this study.

ABSTRACT

In 1983, after a 7-year study of the Chesapeake Bay, the U.S. Environmental Protection Agency (EPA) released a report indicating that the Chesapeake Bay was showing the effects of man-made pollution. Among their findings, eutrophication in the Bay and its tributaries is one of the most important and serious problems. This condition is caused by the excessive inputs of phosphorus and nitrogen to the aquatic system. Moreover, results from a recent study of the upper James River indicate that nutrients not utilized by the algal can be transported into the lower James Estuary and possibly into the Chesapeake Bay (Lung, 1986).

The purpose of the study is to determine the importance of phosphorus loadings from the James River to the Bay by model simulations. Two mathematical models were developed in this research : a hydrodynamic model and a water quality model. The hydrodynamic model is a steady-state, two-dimensional, tidally averaged model, similar to the model developed by Blumberg (1977). The water quality model developed in this study is based on the two-dimensional QUICKEST numerical scheme, which is derived by Hall and Chapman (1985).

Mass balance in the hydrodynamic and water quality models is checked in the analysis. The phosphorus model is then used in model sensitivity analyses and projection of total phosphorus levels in terms of various phosphorus control alternatives. Results from model simulations indicate that only an insignificant portion of phosphorus loads from the James River is transported into the Bay.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

$\alpha_R, \alpha_{RT}, \alpha_L, \alpha_{LB}$: the dimensionless longitudinal dispersion coefficient of the right, top, left and bottom cell faces, respectively.

$\alpha_{TR}, \alpha_T, \alpha_{BL}, \alpha_B$: the dimensionless lateral dispersion coefficient of the right, top, left and bottom cell faces, respectively.

α_x : the dimensionless longitudinal dispersion coefficient with respect to the right and left cell faces.

α_y : the dimensionless lateral dispersion coefficient with respect to the top and bottom cell faces.

C_R, C_T, C_L, C_B : the longitudinal courant number of the right, top, left and bottom cell faces with respect to the longitudinal velocity.

$C_{TR}, C_{RT}, C_{BL}, C_{LB}$: the lateral courant numbers of the right, top, left and bottom cell faces with respect to the lateral velocity.

Δ : the operator of the forward difference.

D : the total water depth, ft.

δ_x, δ_y : the operator for the central difference with respect to the x- and y-direction.

dt_c : the critical time step, sec.

dx , dy : the discrete size with respect to the x- and y- direction.

dt : the discrete size of the time step.

DS : the incremental depth-averaged concentration for each time step, mg/l ft.

η_1, η_2 : the tidal elevation, ft.

FR, FL, FT, FB : advective and diffusive contribution for the depth transport constituent concentration through the right, left, top and bottom cell faces, respectively.

f : twice the value of the vertical component of the earth's rotation, 1/sec.

F : the function dependent on the discrete variables x, y and t.

Γ_x, Γ_y : dispersion coefficient with respect to the x- and y- direction.

g : the acceleration of gravity, ft/ sec^2 .

H : the depth of water with respect to the mean low water water level, ft.

h : the total water depth, ft.

i : the notation for the discrete point in the x- direction.

j : the notation for the discrete point in the y- direction.

k : the bottom friction coefficient, [ ].

K : decay coefficient for the constituent, 1/day.

n : the time level, [ ].

NTIME : the number of time step, [ ].

ϕ : water quality constituent concentration, mg/l.

Φ : the corresponding depth-averaged transport constituent concentration, mg/l ft.

S : source and sink terms of the constituent, mg/l ft/sec.

t : time coordinate, sec.

τ_x^w, τ_y^w : the wind stress component in the x- and y- direction respectively, ft^2/sec^2 .

u : the corresponding depth-averaged longitudinal velocity components, ft/sec.

uD : the corresponding longitudinal volume transport, ft^2 /sec.

u' : the corresponding depth dependent longitudinal velocity component, ft/sec.

v : the corresponding depth-averaged lateral velocity component, ft/sec.

vD : the corresponding lateral volume transport, ft^2 /sec.

v' : the corresponding depth dependent lateral velocity component, ft/sec.

x : the longitudinal coordinate, ft.

y : the lateral coordinate, ft.

1. INTRODUCTION AND PURPOSE

The Chesapeake Bay is a valuable living resource. It is not only for the Bay's productivity but also for its scenic beauty. During the past 15 years, however, its long term health has been deteriorating with dramatic reduction of fish populations. In 1983, after a 7-year study of the Bay, the U.S. Environmental Protection Agency (EPA) released a report which indicated that the Bay was indeed showing the effects of man-made pollution.

Eutrophication in the Chesapeake Bay and its tributaries is one of the most important and serious problems among their findings. This condition is caused by excessive inputs of phosphorus and/or nitrogen to the aquatic system. The result is the productivity and abundance of some undesirable aquatic organisms which quickly deplete dissolved oxygen in the bottom waters. In addition, eutrophication causes much of the turbidity that affects the aesthetic appeal of the Bay waters in many areas. For the past two decades, eutrophication control for the Chesapeake Bay has focused on the reduction of point source phosphorus loads in the Bay region. Phosphorus removal has been implemented at many publicly owned treatment works (POTWs). A quantitative analysis of phosphorus loads to the Chesapeake Bay was described in Lung (1986b).

Lung reported that the point and nonpoint sources in the James River basin in Virginia (Figure 1) contribute a significant amount of phosphorus, approximated 24% to 36%, to the Bay (depending on the hydrologic condition in the basin). Results from a recent modeling study of point source phosphorus control in the James River basin indicated that while present nutrient levels in the upper James River Estuary are adequate to

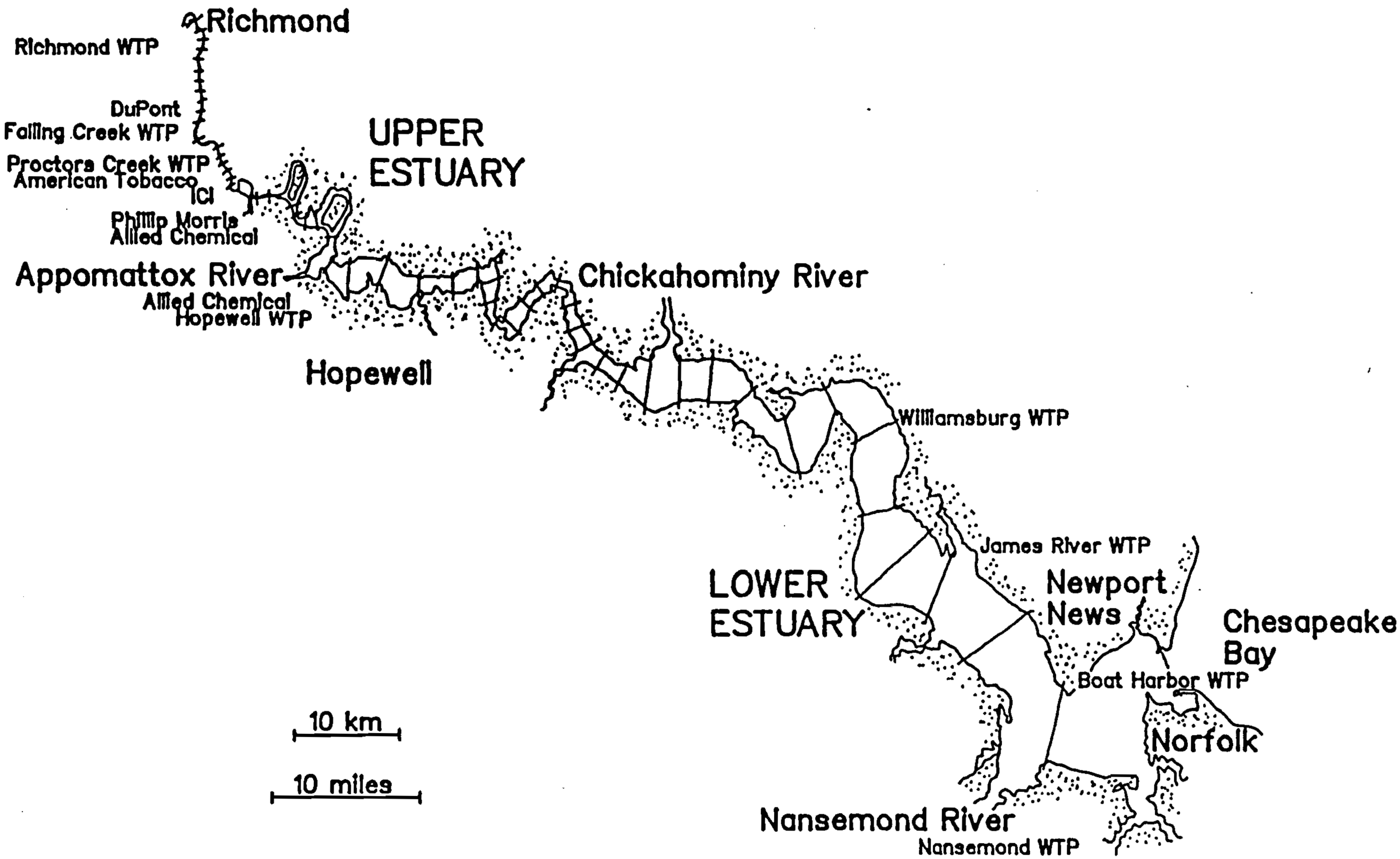


FIGURE 1. The Location of Waste Inputs on the James Basin

support algal growth, a reduction of nutrient inputs by removing phosphorus at POTWs would lead to a phosphorus limiting condition thereby lowering the phytoplankton biomass levels (Lung, 1986a). Further, under the phosphorus removal scenarios, inorganic nitrogen (NH_3, NO_2 and NO_3) concentrations in the estuary would increase in the downstream direction because they would not be utilized by the reduced algal biomass.

Would phosphorus removal in the upper estuary cause a nitrogen increase and result in greater production in the lower estuary and the Chesapeake Bay which may be nitrogen limited? This is an important question in light of the fact that the Virginia Water Control Board has adopted an average monthly limit of 2 mg/L of total phosphorus in the effluent of about 40 POTWs in the Chesapeake Bay drainage basin. Further, a phosphate detergent ban has been in effect in Virginia since January 1, 1988.

Part of the above question has been addressed in a recent report by Lung (1987) who found that increases of inorganic nitrogen in the lower James River Estuary would play a minor role in algal growth. Rather, high turbidity levels in the water column tend to suppress algal growth in the lower estuary.

This study attempts to address the second part of the question and to put the phytoplankton-nutrient dynamics in the James Estuary and the Chesapeake Bay into perspective by quantifying the fate and transport of phosphorus in the Bay as a result of the James River input.

The investigation of the fate and transport of phosphorus inputs in the study area is achieved by numerical simulations. There are two parts of the mathematic modeling framework developed in this study : a hydrodynamic model and a water quality model for phosphorus based on the mass transport pattern derived from the first model. The water quality model also incorporates the effects of phosphorus loading from other tributaries to the Chesapeake Bay.

2. THE CHESAPEAKE BAY AND THE JAMES RIVER

The Chesapeake Bay is a complex estuarine system comprised of the Bay proper and its tributaries. The whole Bay region (Figure 2) stretches over 64,000 square miles, ranging 200 miles from north to south and 4 to 30 miles wide. The depth of the Bay varies from as much as 175 feet (off the southern tip of Kent Island), to shallow tidal marshes that are exposed at low tides. The average depth of the bay is estimated to be 27 feet, with a surface area of approximately 76 billion square cubic feet.

The Bay receives freshwater from more than 150 creeks and 8 major rivers. Principal tributaries are the Susquehanna River at the head, the Potomac River at the Maryland-Virginia border, the Rappahannock River in Virginia and the James River at Hampton Roads, Virginia. The monthly flow at the mouth of Chesapeake Bay ranges from 7,800 cfs to 325,000 cfs based on the historical record of estimated streamflow entering the Bay from each of the tributaries by the U.S. Geological Survey (USGS). The range of tidal stages is greatest at the mouth of Chesapeake Bay which is the junction with the Atlantic Ocean, with a range of approximately 2.5 ft, and is about 1 ft at the head of the Bay. The effect of winds may be important, which causes tidal heights and currents to vary several times about the normal.

2.1 Waste Loading Inputs - Point And Nonpoint Sources to the Bay

The Bay is the recipient of the industrial and treated municipal waste effluents, combined sewer overflows , groundwater discharges and residuals contained in rainwater runoff. These waste loads enter the Bay from major tributaries and the immediate

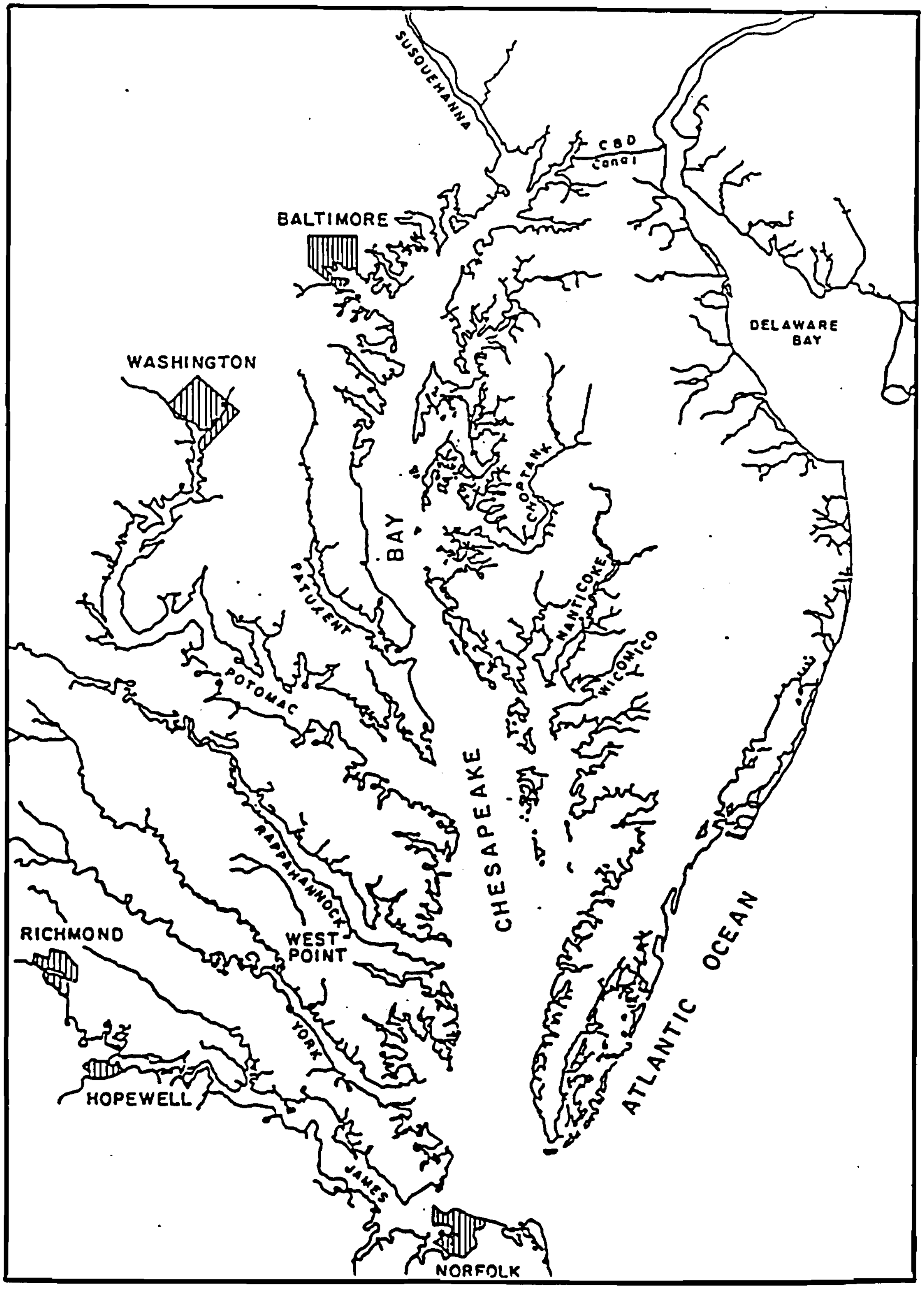


FIGURE 2. The Chesapeake Bay And the Location of the Principle Point Source

Inputs

drainage. Furthermore, the Bay receives nutrient inputs from atmospheric sources via direct precipitation on the Bay's water surface. Figure 2 shows the location of the principal point source inputs, the municipal and industrial wastewater treatment plants located in major urban centers.

Depending upon the time of the year, these waste inputs can be accumulated in the Bay. For example, during the summer months and the other periods of low rainfall, the point sources are significant due to the low dilution of effluent. However, the nonpoint sources remaining on the ground are not so important due to the non-washoff effect. During the winter and the early spring months and periods of significant rainfall, the importance of point source effluents decreases due to increased dilution and associated nonpoint loads. Figure 3 shows the relative contribution of point and nonpoint sources of nutrient during dry, average and wet years (USEPA, 1983). It is seen that point sources of phosphorus contributes about 69% of total phosphorus input during a dry year and would reduce to approximately 36% of the total load during a wet year. On the other hand, point sources contribute 38% of the total nitrogen to the Bay in a dry year and about 19% in a wet year.

2.2 Eutrophication Control for the Bay

In 1976, Congress directed EPA to conduct a study of the Chesapeake Bay. After a 7-year study, EPA found that the Bay is indeed showing the man-made pollution. Subsequently, a restoration program for the Bay was developed in 1983. The Chesapeake Bay Commission, U.S. EPA, the State of Maryland, the Commonwealths of Virginia and Pennsylvania, and the District of Columbia signed a Chesapeake Bay Agreement in

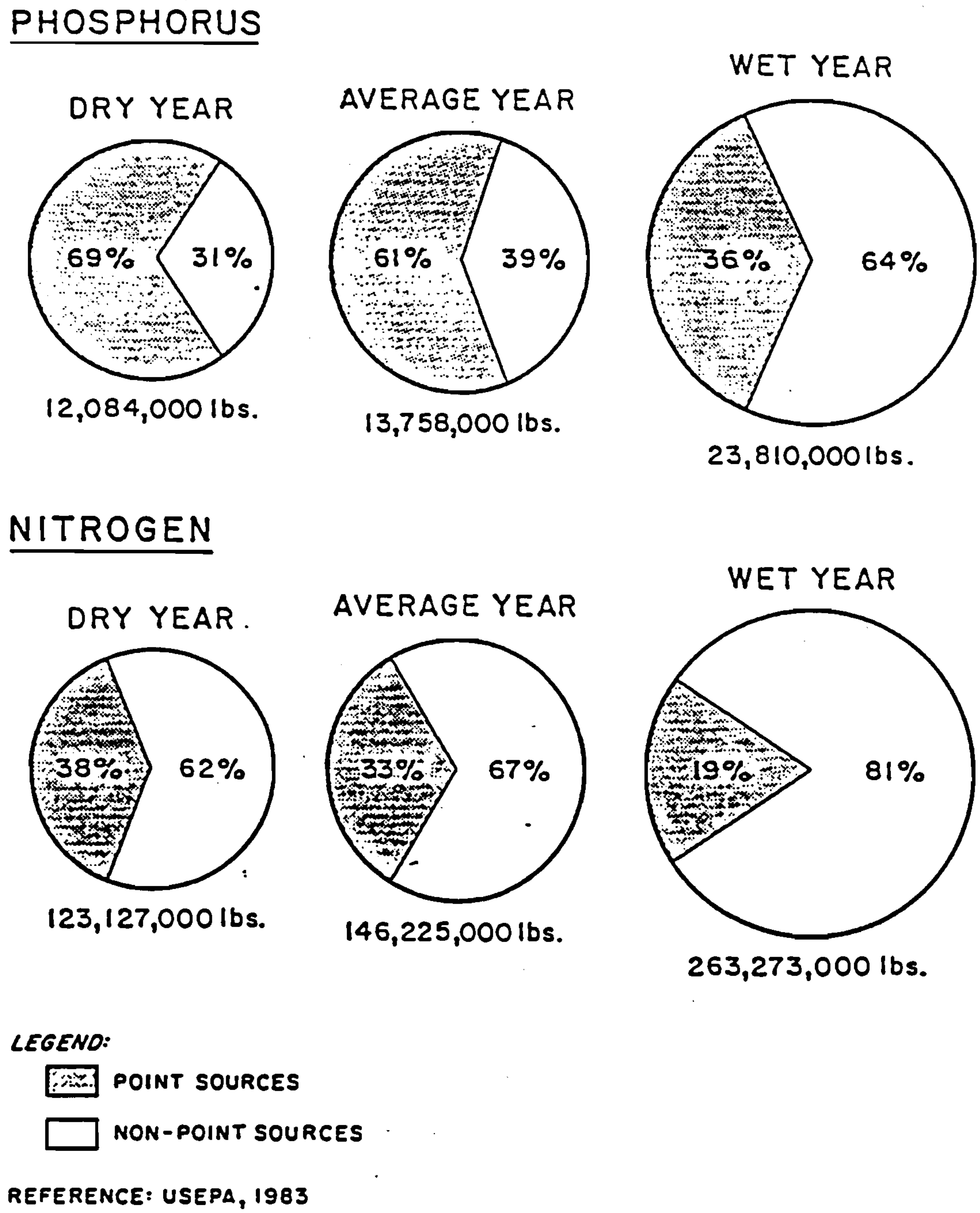


FIGURE 3. Annual Point And Nonpoint Loadings to the Chesapeake Bay System

December 1983. They agreed to establishing a structure to oversee the cooperative and comprehensive measures necessary to restore the Bay.

The restoration program of the Bay includes the formulation of the planning, data management, monitoring and modeling. Especially, the monitoring program, begun in 1984, by the Chesapeake Bay Executive Council, comprises over 160 stations and represents combined efforts of numerous states, federal agencies and institutions. For example, over twenty physical, chemical and biological characteristics of water quality have been monitored for approximately 20 times a year in the Bay proper and major tributaries.

It was found that eutrophication in the Bay and its tributaries is one of the most important problems. Nutrients reductions have been the major focus of the Bay restoration program. The Scientific and Technical Advisory Committee (STAC) of the Bay Program has reviewed overall nutrient reduction strategies throughout the basin. STAC concluded that reductions of nitrogen and phosphorus loadings from nonpoint sources and phosphorus loadings from point sources should be addressed. Subsequently, water quality managers could develop reduction scenarios for eutrophication control. In addition, for the past two decades, the reduction of the point source phosphorus loads (primarily from POTWs) has been the focus for controlling eutrophication in the Bay and its tributaries. Currently, phosphorus removal occurs at many POTWs that discharge to several major river basin in the Chesapeake Bay region.

A new Chesapeake Bay agreement, which was signed in December 1987, commits the Bay states and EPA to an ambitious agenda of initiatives, including a pledge to reduce nutrient input of the Bay by 40% by the close of the century. One of the strong commitments of the new agreement is to develop, calibrate, and validate a three-dimensional water quality model of the Bay by 1991. The model will be used to guide how the 40% nutrient reduction can be achieved.

2.3 Phosphorus from the James River Basin

Assuming that the phosphorus loads from the James River Basin are 100% delivered to the Bay, the James River basin would contribute about 15% to 30% of the Bay phosphorus input depending upon the hydrologic condition (Lung, 1986a). Figure 1 shows major phosphorus dischargers in the James River basin. Table 1 presents a summary of major wastewater loadings on September 20, 1983 to the James River. One of the reasons that the James River basin contributes such a large portion of phosphorus loads is none of the POTWs in the basin currently practices phosphorus removal. Besides, there was no other form of nutrient control existing in the James River basin until this year. A phosphate detergent ban has been in effect in Virginia since January 1, 1988. Preliminary monitoring data indicates that the ban has reduced about 25% to 35% of the phosphorus concentration in the effluent.

Discharger	$CBOD_{40}$	Org.N	NH_3	NO_2+NO_3	Total P	Org.P	Ortho-P
Richmond	4512	4927	3916	2332	2328	144	2184
DuPont	202	230	38	9	5	2	2
Falling Creek	714	336	116	745	502	111	390
Proctors Creek	2602	208	103	33	179	25	154
Reynolds Metals	1	3	0	2	2	2	0
American Tobacco	60	27	1	31	6	0	6
ICI	31	8	0	4	1	1	0
Philip Morris	368	27	6	267	106	39	66
Allied-Chester	2480	42	3	61	9	6	3
Allied-Hopewell	12680	3363	2069	2349	80	66	13
Hopewell	8929	7048	5904	326	347	205	142
Williamsburg	229	15	196	65	162	125	37
James River	436	221	878	25	534	187	347
Boat Harbor	410	340	2719	13	867	167	700
Nansemond	770	178	938	34	362	12	350
Army Base	413	393	2063	11	569	263	306
Lamberts Point	21893	520	3087	17	418	332	86

TABLE 1. Major Waste Loading for September 20, 1983 Condition

3. CIRCULATION MODELING OF THE BAY

3.1 Hydrodynamic Equations And Finite Difference Approximation

The main purpose of the circulation model is to provide estimates of mass transport for use in the water quality analysis. The original framework was developed by Blumberg (1977). The basic equations for the circulation model are the shallow water equations. Let the coordinates be horizontal rectangular as well as x and y be increasing eastward and northward respectively. The coordinate system is shown in Figure 4. The hydrodynamic equations adopted from Blumberg (1977) are

$$\frac{\partial uD}{\partial t}+\frac{\partial u^2 D}{\partial x}+\frac{\partial uvD}{\partial y}-fvD+gD\frac{\partial \eta}{\partial x}=\tau_x^w-ku(u^2+v^2)^{1/2} \tag{1}$$

$$\frac{\partial vD}{\partial t}+\frac{\partial vuD}{\partial x}+\frac{\partial v^2 D}{\partial y}+fuD+gD\frac{\partial \eta}{\partial y}=\tau_y^w-kv(u^2+v^2)^{1/2} \tag{2}$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial uD}{\partial x}+g\frac{\partial vD}{\partial y}=0 \tag{3}$$

In which

u = the corresponding depth averaged horizontal velocity component.

v = the corresponding depth averaged lateral velocity component.

g =the acceleration of gravity.

τ_x^w = the horizontal wind stress component.

τ_y^w = the lateral wind stress component.

k = the bottom friction coefficient.

f = twice the value of the vertical component of the earth's

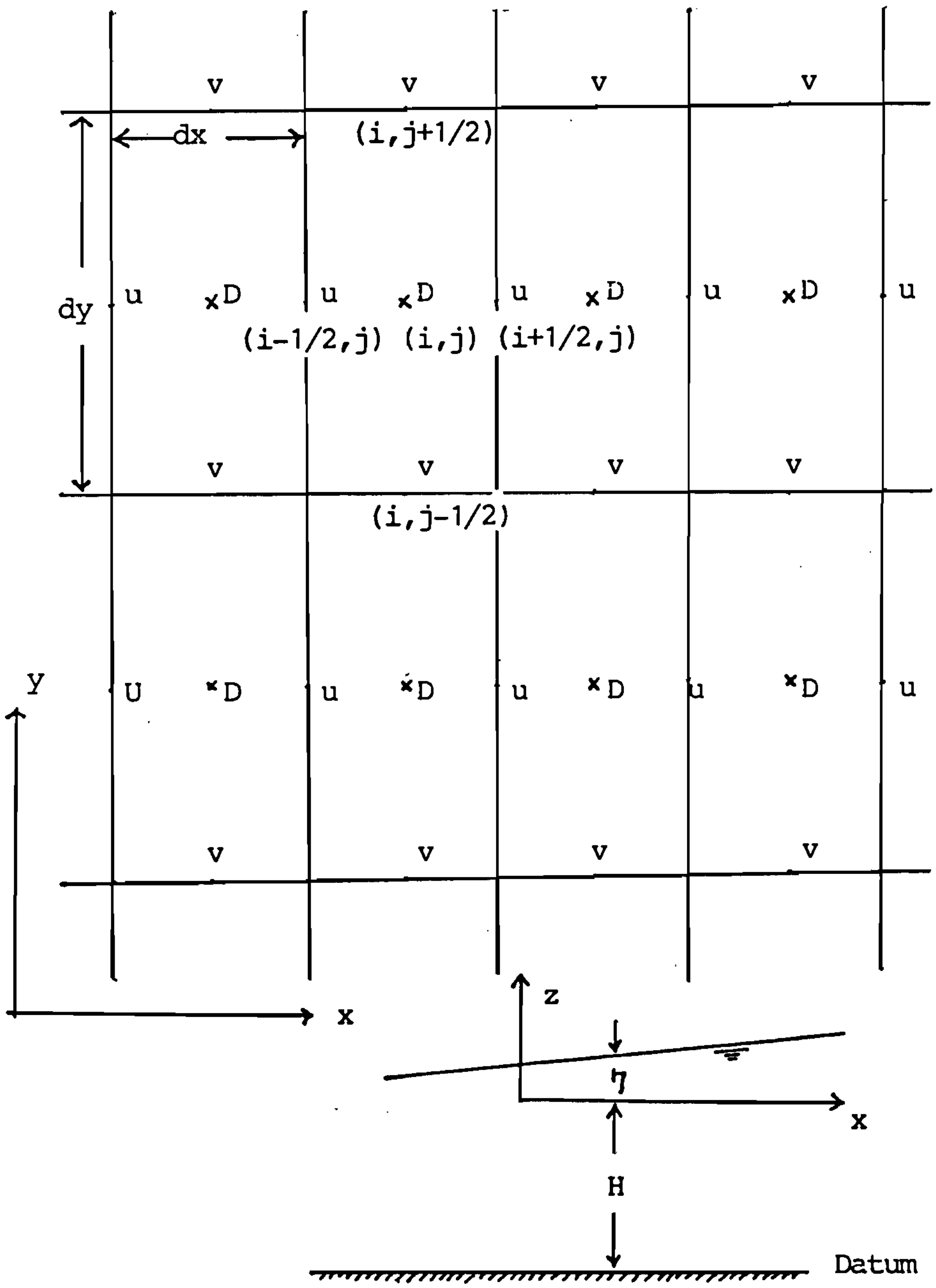


FIGURE 4. Arrangement of Variables on Finite Difference Grids

rotation.

η= the free surface elevation.

H = the depth of water with respect to the mean low water level.

D = the total water depth.

The velocity components u, v are defined as

$$u = \frac{1}{D}\int_{-H}^{\eta} u' dz; \qquad v = \frac{1}{D}\int_{-H}^{\eta} v' dz \tag{4}$$

in which

u' = the corresponding depth dependent horizontal velocity component.

v' = the corresponding depth dependent lateral velocity component.

uD = the corresponding longitudinal volume transports.

vD = the corresponding lateral volume transports.

The incompressible and homogeneous flow conditions are assumed in the formulations. And the density variations in the water column is neglected so that constant density is assumed in the vertical direction. The boundary conditions applicable to Eqs. 1, 2 and 3 are the specification of the tidal elevation at the open boundaries and the discharges of water into the system along the other boundaries. In addition, the normal velocity components of the volume transport have to vanish at the coast if there is no inflow.

Numerical techniques were employed for obtaining the solutions to the coupled nonlinear differential equations. Firstly, the variables u, v and D are defined on a grid mesh as shown in Figure 4. Since the sum of H and η is equal to D, they two are at the same location of D. Because a north-south boundary is chosen to coincide with the u points and an east-west boundary to coincide with the v points, the boundary condition of no normal flow through the coast is easily accomplished.

To derive the differential scheme of these nonlinear equations, the following operators are employed :

$$\overline{F(x,y,t)}=\frac{F(x+dx/2,y,t)+F(x-dx/2,y,t)}{2} \tag{5}$$

$$\delta_x F(x,y,t)=\frac{F(x+dx/2,y,t)+F(x-dx/2,y,t)}{dx} \tag{6}$$

$$\delta_x \overline{F(x,y,t)}^x=\frac{F(x+dx,y,t)-F(x-dx,y,t)}{2dx} \tag{7}$$

$$\overline{F(x,y,t)}^{xy}=\overline{\overline{F(x,y,t)}^x}^y \tag{8}$$

in which F is any function of the discrete variables x,y,t; and dx is the grid spacing. Similar operators for variables y and t can be defined. The final difference scheme derived by Blumberg (1977) is therefore written as

$$\frac{(\overline{D}^x u)^{n+1}-(\overline{D}^x u)^{n-1}}{2dt}+\delta_x(\overline{\overline{D}^x u}^x\,\overline{u}^x)+\delta_y(\overline{\overline{D}^y v}^x\,\overline{u}^y)-f\overline{\overline{D}^y v}^{xy}+$$
$$g\overline{D}^x\delta_x\eta-\tau_x^w+k[u(u^2+(\overline{v}^{xy})^2)^{1/2}]^{n-1}=0 \tag{9}$$

$$\frac{(\overline{D}^y v)^{n+1}-(\overline{D}^y v)^{n-1}}{2dt}+\delta_x(\overline{\overline{D}^x u}^y\,\overline{v}^x)+\delta_y(\overline{\overline{D}^y v}^y\,\overline{v}^y)+f\overline{\overline{D}^x u}^{xy}+$$
$$g\overline{D}^y\delta_y\eta-\tau_y^w+k[v(v^2+(\overline{u}^{xy})^2)^{1/2}]^{n-1}=0 \tag{10}$$

$$\frac{\eta^{n+1}-\eta^{n-1}}{2dt}+\delta_x(\overline{D}^x u)+\delta_y(\overline{D}^y v)=0 \tag{11}$$

in which the superscripts n+1 and n-1 indicate the time step. Terms at time step n are without a superscript. The frictional term are lagged one time step to avoid numerical instability. Eqs. 9, 10 and 11 are rearranged as followed :

$$(\bar{D}^x u)^{n+1} = (\bar{D}^x u)^{n-1} - 2dt[\delta_x(\overline{\bar{D}^x u}^x \bar{u}^x) + \delta_y(\overline{\bar{D}^y v}^x \bar{u}^y) - f\overline{\bar{D}^y v}^{xy} +$$

$$g\bar{D}^x \delta_x \eta - \tau_x^w + k(u(u^2 + (\bar{v}^{xy})^2)^{1/2})^{n-1}] \tag{12}$$

$$(\bar{D}^y v)^{n+1} = (\bar{D}^y v)^{n-1} - 2dt[\delta_x(\overline{\bar{D}^x u}^y \bar{v}^x) + \delta_y(\overline{\bar{D}^y v}^y \bar{v}^y) + f\overline{\bar{D}^x u}^{xy} +$$

$$g\bar{D}^y \delta_y \eta - \tau_y^w + k(v(v^2 + (\bar{u}^{xy})^2)^{1/2})^{n-1}] \tag{13}$$

$$\eta^{n+1} = \eta^{n-1} - 2dt[\delta_x(\bar{D}^x u) + \delta_y(\bar{D}^y v)] \tag{14}$$

$(\bar{D}^x u)^{n+1}$, $(\bar{D}^y v)^{n+1}$ and η^{n+1} are calculated by eqs. 12 to 14. Then, u^{n+1} and v^{n+1} are derived by $(\bar{D}^x u)^{n+1}$ and $(\bar{D}^y v)^{n+1}$, respectively. The numerical integrations start with a forward time step and then are followed by the leap-frog scheme. That is, at n = 1, the factor 2dt in Eqs. 12, 13 and 14 is modified to be dt. By using Eqs. 5, 6, 7 and 8, the individual term in Eqs. 12, 13 and 14 can be expanded as;

$$\delta_x(\overline{\bar{D}^x u}^x \bar{u}^x) = [((\bar{D}^x u)_{i+3/2,j} + (\bar{D}^x)_{i+1/2,j})(\bar{u}^x)_{i+1,j} - \tag{15}$$

$$((\bar{D}^x u)_{i+1/2,j} + (\bar{D}^x u)_{i-1/2,j})(\bar{u}^x)_{i,j}]/2dx$$

$$\delta_y(\overline{\bar{D}^x v}^x \bar{u}^y) = [((\bar{D}^y v)_{i+1,j+1/2} + (\bar{D}^y)_{i,j+1/2})(\bar{u}^y)_{i+1/2,j+1/2} - \tag{16}$$

$$((\bar{D}^y v)_{i+1,j-1/2} + (\bar{D}^y v)_{i,j-1/2})(\bar{u}^y)_{i+1/2,j+1/2}]/2dy$$

$$\overline{\bar{D}^y v}^{xy} = [(\bar{D}^y v)_{i+1,j+1/2} + (\bar{D}^y v)_{i,j+1/2} + (\bar{D}^y v)_{i+1,j-1/2} + \tag{17}$$

$$(\bar{D}^y v)_{i,j-1/2}]/4$$

$$\bar{v}^{xy} = [(\bar{v}^x)_{i+1/2,j+1/2} + (\bar{v}^x)_{i+1/2,j-1/2}]/2 \tag{18}$$

$$\delta_x(\overline{\bar{D}^x u}^y \bar{v}^x) = [((\bar{D}^x u)_{i+1/2,j-1} + (\bar{D}^x u)_{i+1/2,j})(\bar{v}^x)_{i+1/2,j-1/2} - \tag{19}$$

$$((\overline{D}^x u)_{i-1/2,j} + (\overline{D}^x u)_{i-1/2,j})(\overline{v}^x)_{i-1/2,j-1/2}]/2dx$$

$$\delta_y(\overline{\overline{D}^y v}^y \overline{v}^y) = [((\overline{D}^y v)_{i,j+1/2} + (\overline{D}^y v)_{i,j-1/2})(\overline{v}^y)_{i,j} - \tag{20}$$

$$((\overline{D}^y v)_{i,j-3/2} + (\overline{D}^y v)_{i,j-1/2})(\overline{v}^y)_{i,j-1}]/2dy$$

$$\overline{\overline{D}^x u}^{xy} = [(\overline{D}^x u)_{i+1/2,j-1} + (\overline{D}^x u)_{i-1/2,j-1} + (\overline{D}^x u)_{i+1/2,j} + \tag{21}$$

$$(\overline{D}^x u)_{i-1/2,j}]/4$$

$$\overline{u}^{xy} = ((\overline{u}^y)_{i-1/2,j+1/2} + (\overline{u}^y)_{i+1/2,j+1/2})/2 \tag{22}$$

Eqs. 15, 16, 17 and 18 are derived with respect to the central point (i+1/2,j). However Eqs. 19, 20, 21 and 22 are with respect to the central point (i, j-1/2). The grid points used to make the interpolation of each of the u(i+1/2, j), v(i,j-1/2) and D(i,j) are shown in Figure 5 . The notation is implemented in the computer program code by shifting half a step forward with respect to i and j for u and v, respectively. Figure 6 shows the notation defined in the program coding of the finite difference equations.

To avoid stability problems of the finite difference scheme, a simplied method is used. Two numerical stability criteria are :

1. $dt \le [\sqrt{gD_{max}}\,(1/dx + 1/dy)]^{-1}$ (23)

2. $dt < 1/f$ (24)

The right hand side of Eq. 23 is equal to the critical time step dt_c, which must be larger than the time step employed.

There are additional boundary conditions required at the open boundary with regard to the finite difference scheme. For the abrupt change in width of water body at the open

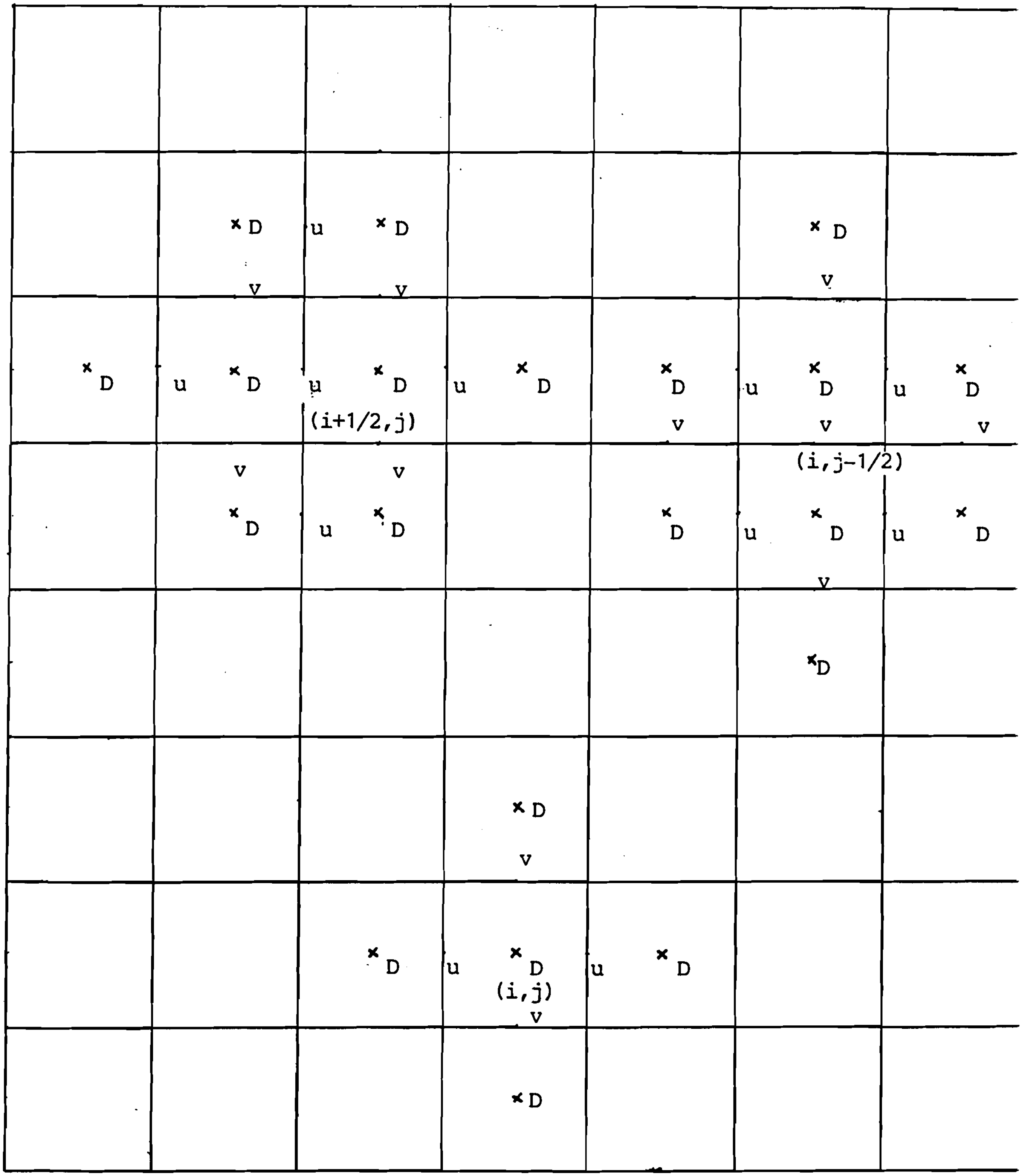


FIGURE 5. Grids Points for the 2-D Hydrodynamic Computation Lattice

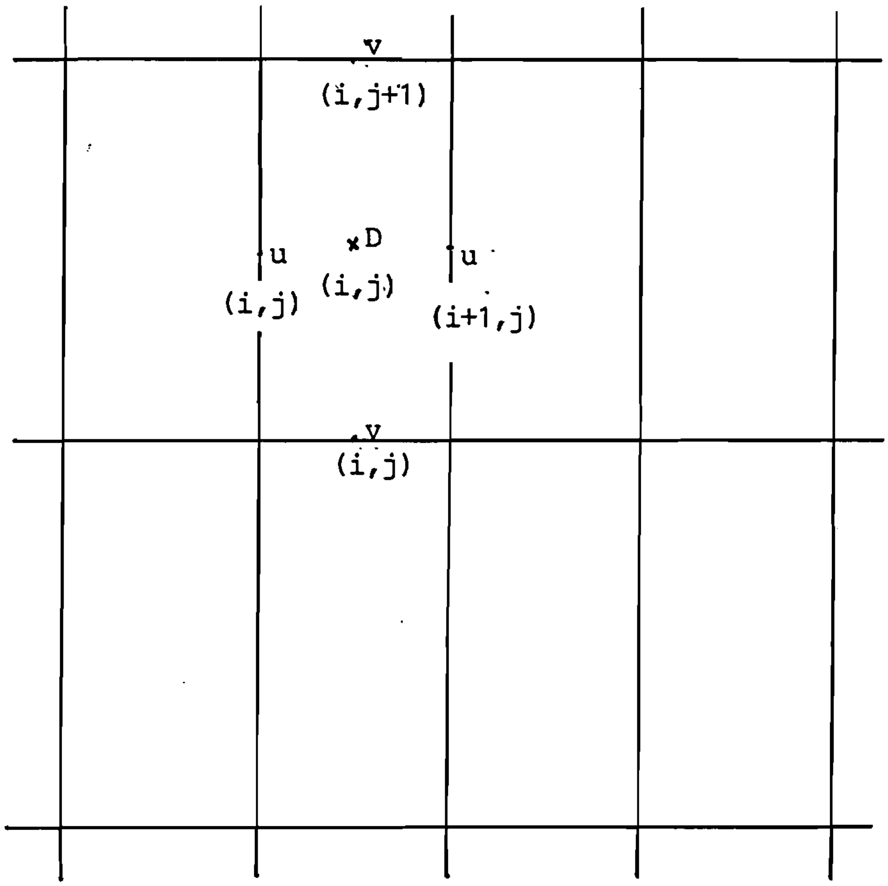


FIGURE 6. The Notation of Grid Variables in Programming the Models

boundary, it is assumed that the volume transports are perpendicular to the open boundary and that there is no momentum flux imported to the interior from the exterior region. For example, considering a north-south open boundary, the v component of the volume transport is equal to zero because there are no v points coincided with the boundary. In addition, the u^2D " momentum " just outside of the interior region is much smaller than that " momentum " just inside the interior region, therefore, this condition eliminates the need to specific u values at the grid points just outside of the interior region (a distance dx/2 away from the input forcing function at the open boundary). The diagram for this example is shown in Figure 7. In addition, the water depth of the exterior region is assumed to be the same as that of the adjacent interior grid when calculating the velocity components at the boundaries of water discharges.

3.2 Application to the Chesapeake Bay

The grid system used for the computation in the Chesapeake Bay and the James River hydrodynamic model is presented in Figure 8. The boundaries of the Chesapeake Bay are defined to fit on a grid 25 by 48 points and that of the James River 24 by 9 points. The Chesapeake Bay and the James River are separated to two systems for efficient use of computer memory. That is, the storage space of a 50 by 50 matrix is more than that of 25 by 50 plus 25 by 10 matrices. Therefore, the program has to combine the grid point values between the junction of the two systems. For numerical simulations, the horizontal grid sizes are dx=9986.67 ft and dy= 20597.5 ft. The mean low water level (H) is based upon the bathymetric chart which is estimated by Goldsmith, Sutton and Williams at the Virginia Institute of Marine Science (1977). With this grid size, a time step of 60 sec is needed to satisfy the stability criterion, Eq 23. The other parameters and

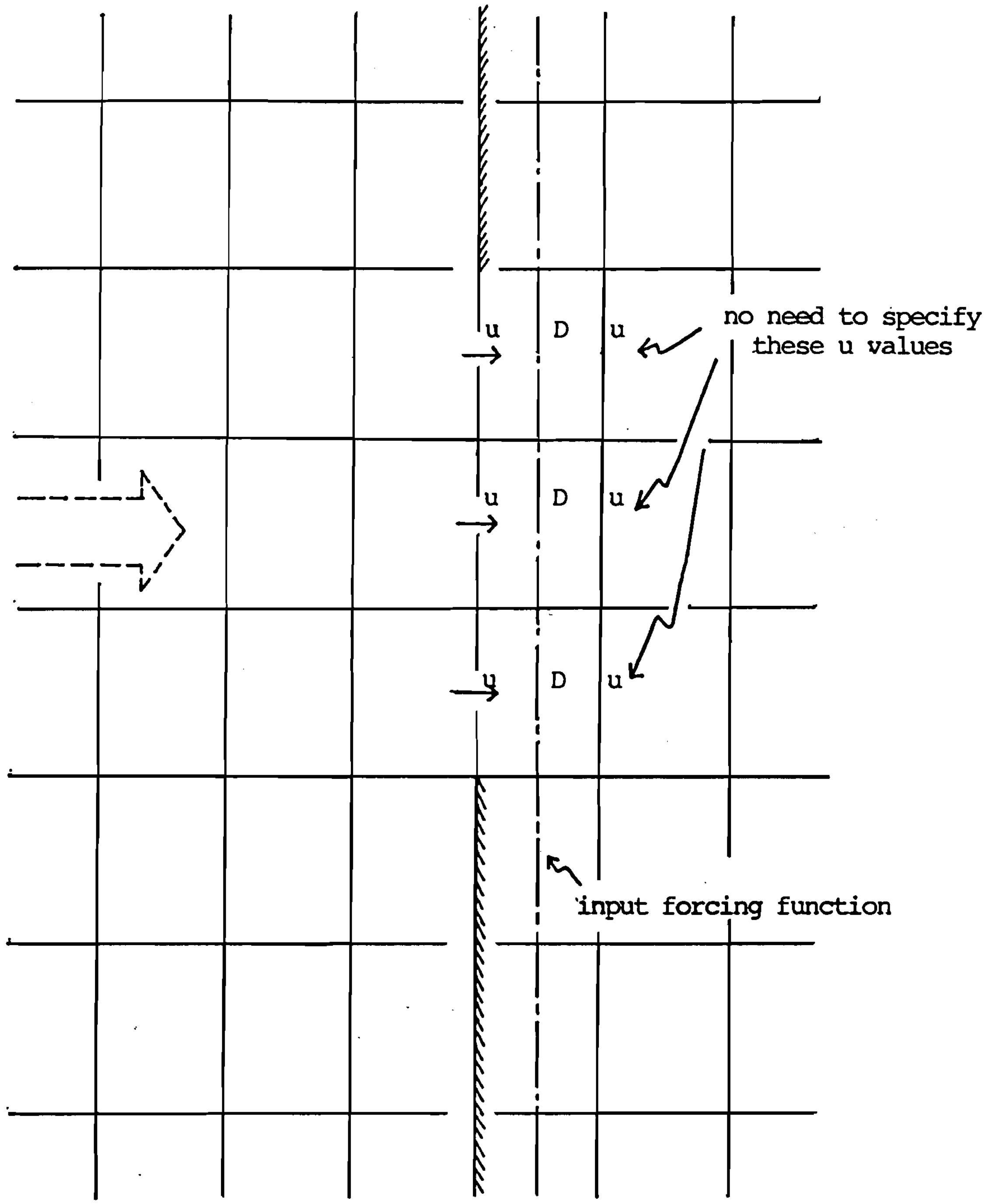


FIGURE 7. The Open Boundary at the Mouth of the Bay

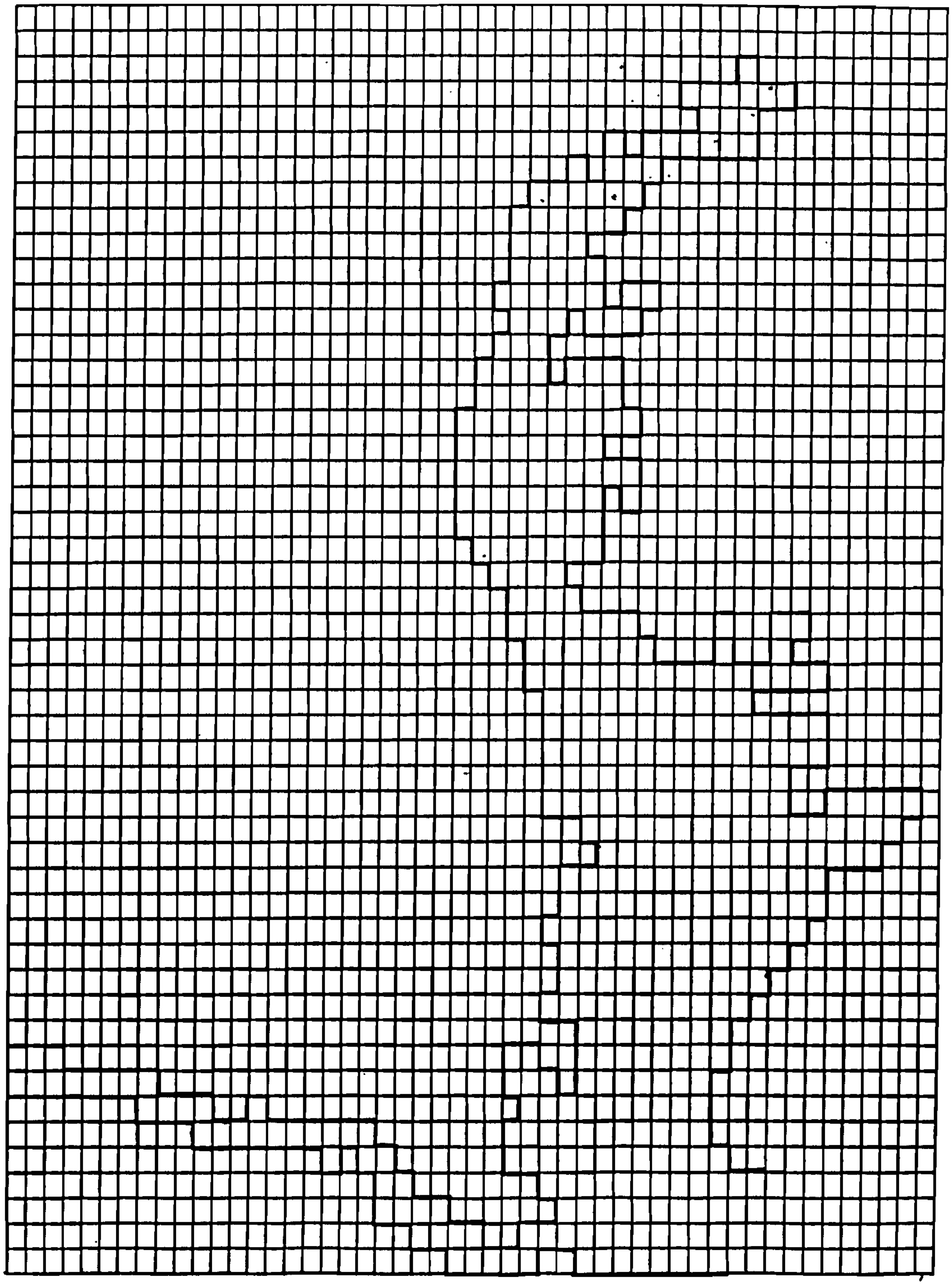


FIGURE 8. Computational Grid System for the Chesapeake Bay

discharge inflows obtained from Blumberg (1977) are summarized in Table 2. Freshwater inflows from the Susquehanna River, Potomac River and Rappahannock River were incorporated in the model although the tributaries were not modeled.

Along the open boundary of the the Atlantic Ocean, the tidal elevation η, prescribed from values of the tidal table given by the National Ocean Survey for a tidal cycle (12.51 hrs) beginning April 10, 1976 at 16.72 hrs after midnight is graphed in Figure 9. The input forcing function for the tidal control elevation is divided into 2 parts :

$$\eta_1 = 1.51 \cdot COS\left(\frac{\pi t}{T1}\right) + 1.31 \qquad 0 < t < T1 \tag{25}$$

$$\eta_2 = -1.54 \cdot COS\left(\frac{\pi(t - T1)}{T2}\right) + 1.34 \qquad T1 < t < T2 \tag{26}$$

in which T1= 5.91 hrs and T2= 6.60 hrs. Therefore there are almost 750 time steps per tidal cycle. Besides, the velocity component is zero along the coast (the closed boundary condition). Since the model will reach a dynamic steady-state condition following constant forcing function, the initial values of velocity components and surface elevation (η) are set to zero, which make no effect on the results. The data input is presented in Appendix 1.

Due to the irregular shape of the simulation domain, a grid search system was established. This function apparently reduces the computer time because the hydrodynamic and/or water quality calculation are just executed within the boundaries. Two one-dimensional arrays, IP(M) and NP(M), in which M=50 for the Chesapeake bay system and M=10 for the James River system, are set . The value of IP(J) is the column index of the grid point that is the first one to do the calculation at J row, and NP(J) presents the

PARAMETER	VALUE
k	0.0025
f 1/sec	0.00009
τ_x^w τ_y^w	0
g lbf/sec2	32.2
Q(1) cfs (Susquehanna river)	8.21E4
Q(2) cfs (Potomac river)	3.11E4
Q(3) cfs (James river)	2.96E4
Q(4) cfs (Rappahannock river)	1.64E4

TABLE 2. Summary of Parameters And Boundary Condition in the Circulation Model

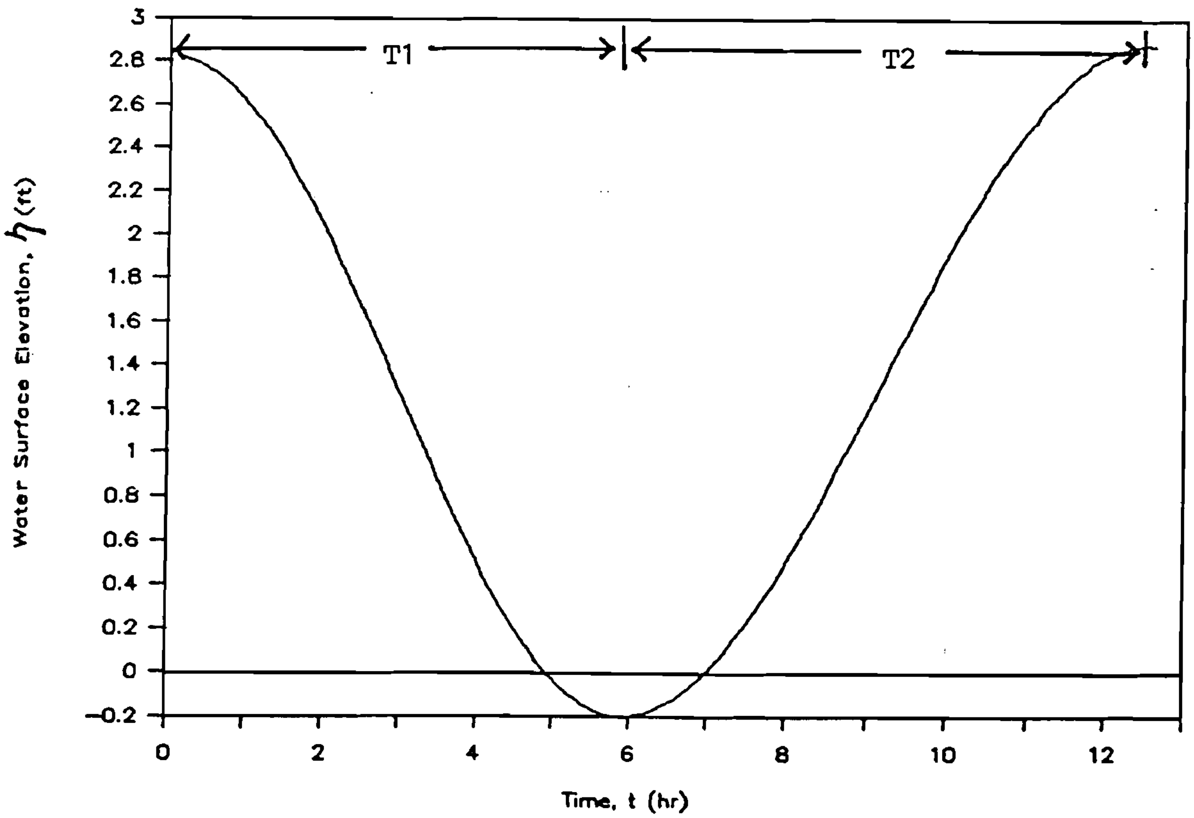


FIGURE 9. Boundary Condition at Atlantic Ocean Junction

number of grid points after column IP(J) at J row that are within the system. However, the variables on the other grids, which are not included in the grid search system, have to be calculated separately. IP(M) and NP(M) are shown the input list in Appendix 1. Appendix 2 presents the program list for the circulation and the water quality simulations.

3.3 Model Results

The hydrodynamic model was first tested to satisfy the theory of mass balance for water. The test method is to put the freshwater input (8.0E6 cfs) at the head (fresh inflow of the Susquahanna River) of the Bay and the tidal control (Figure 9) at the open boundary of Atlantic Ocean. The model was run for 120 time steps (2 hrs). The water volume of fresh inflows and tidal input should be the same as the increase of water volume within the simulation area at the last time step theoretically. The result appears that there is only 0.12 % error for these two quantities (the volume of fresh inflow and the tidal input is 48,389,381,807 ft^3. And the increase of volume within the boundary in the end is 48,331,336, 421 ft^3).

Figure 10, 11 and 12 show the model calculated velocity over one tidal cycle at 2-hr intervals of the 13th tidal cycle. It presents the exactly physical phenomonon of tidal control. During the 12 hrs (that is, almost one tidal cycle), the water transport reverses its direction after a half tidal cycle roughly. Currents at the lower portion of the Bay show the condition of the tidal elevation at the mouth. Figure 13 presents the tidally averaged volume transport vectors at the 12th and the 13th tidal cycles. Both of them are shown the same current conditions. Thus, the model has reached a dynamic steady-state condition after the tidal forcing function is repeated 12 times.

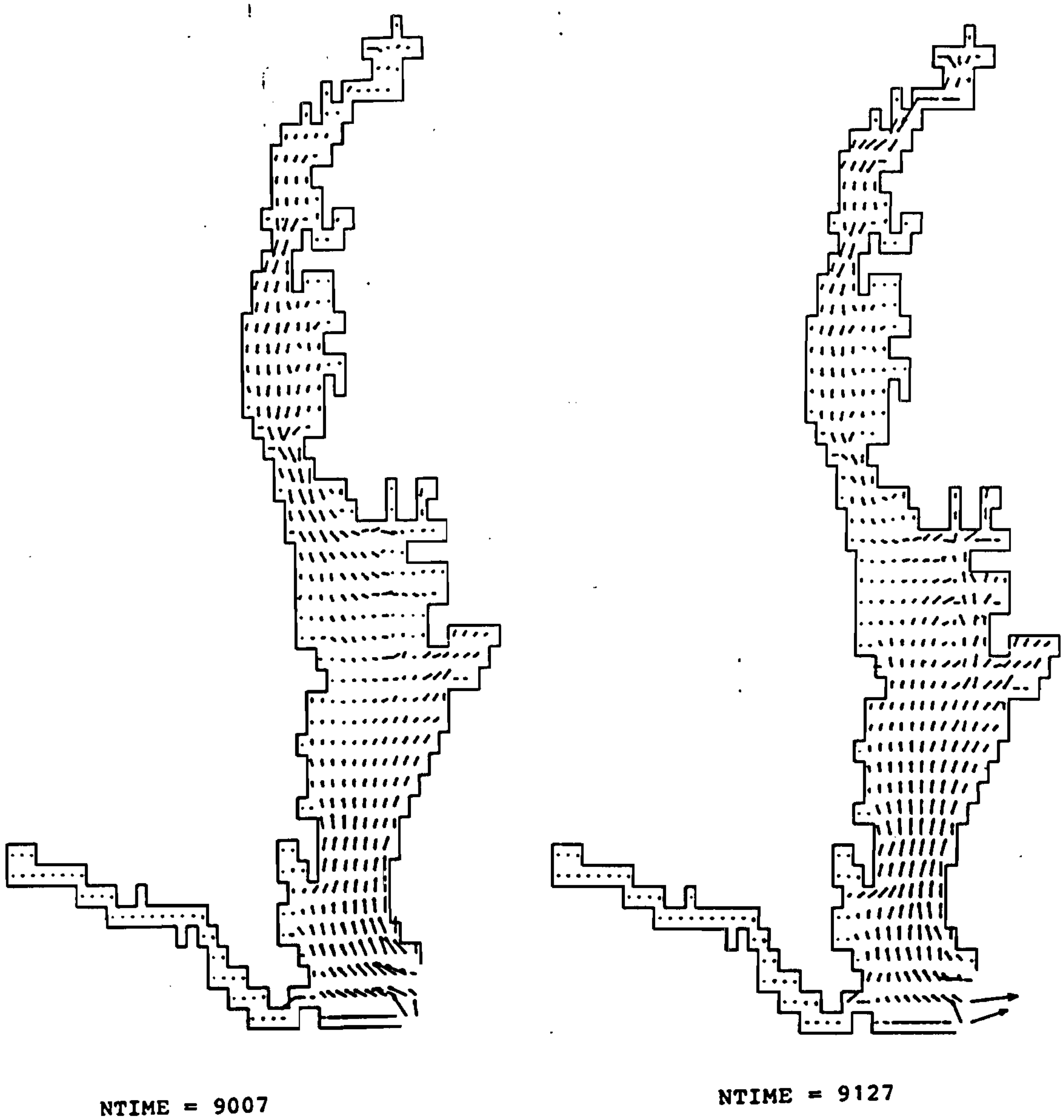


FIGURE 10. Simulated Velocity Vectors at 2-hr Intervals

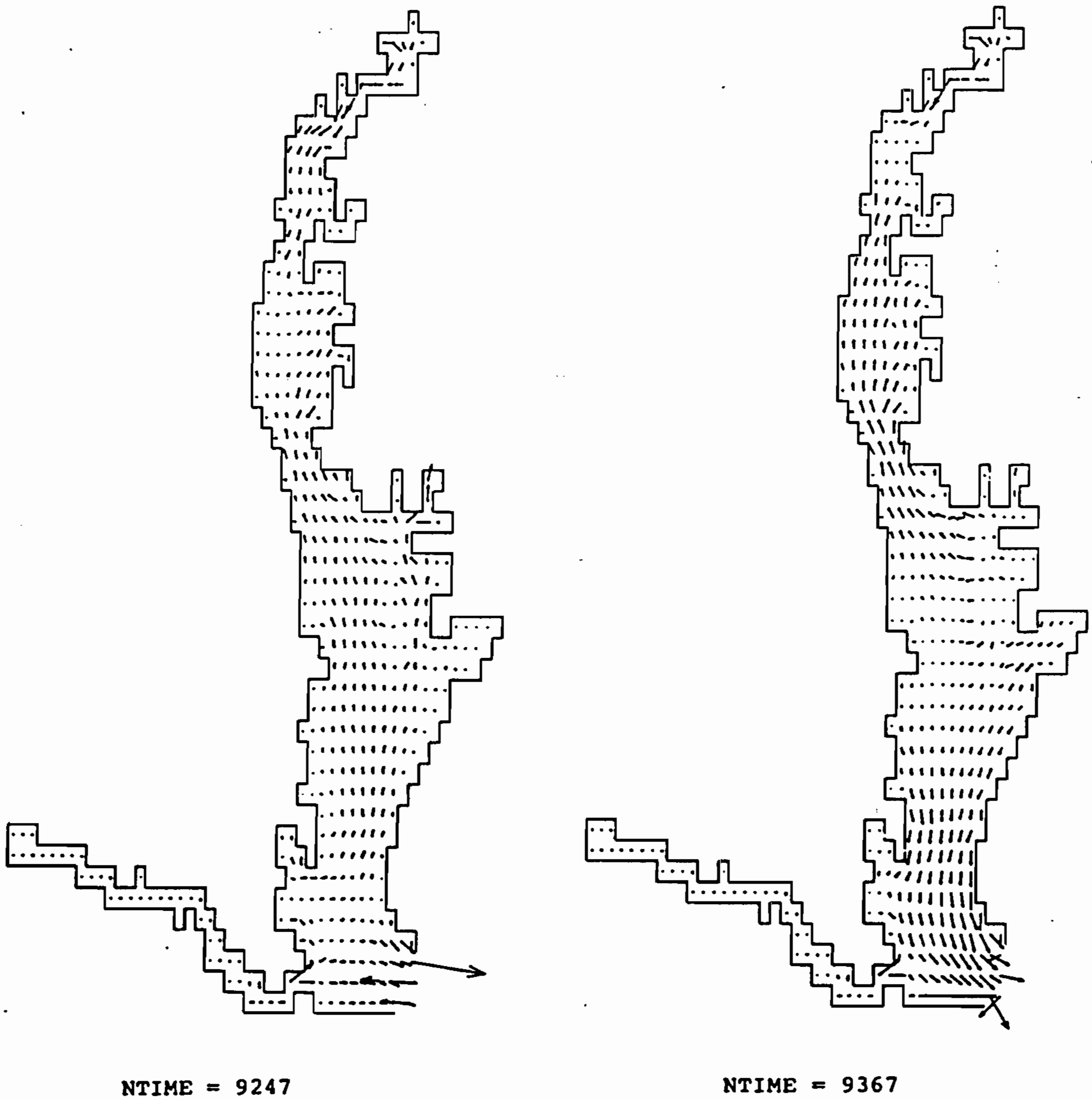


FIGURE 11. Simulated Velocity Vectors at 2-hr Intervals(Continued)

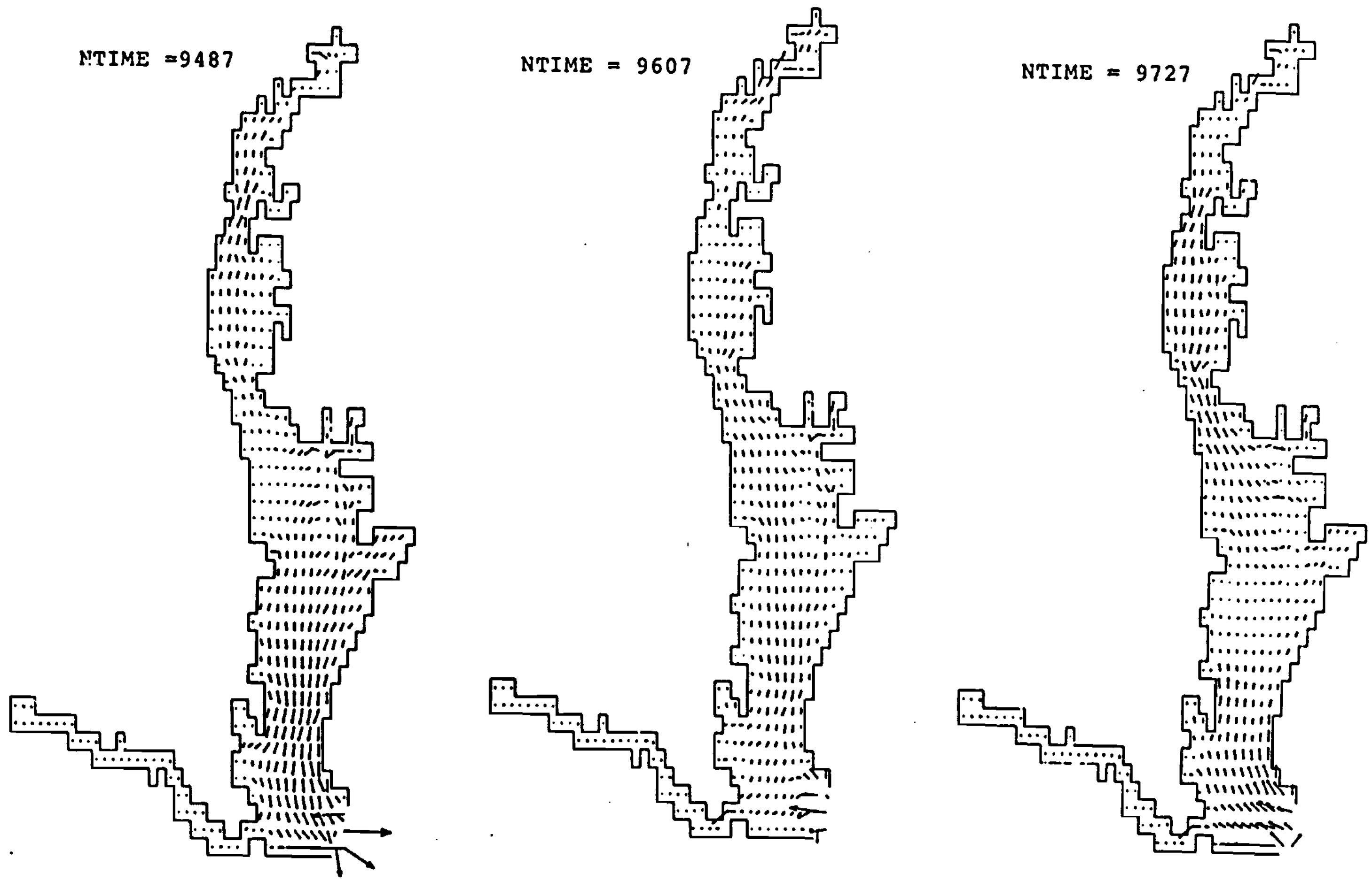


FIGURE 12. Simulated velocity Vectors at 2-hr Intervals(Continued)

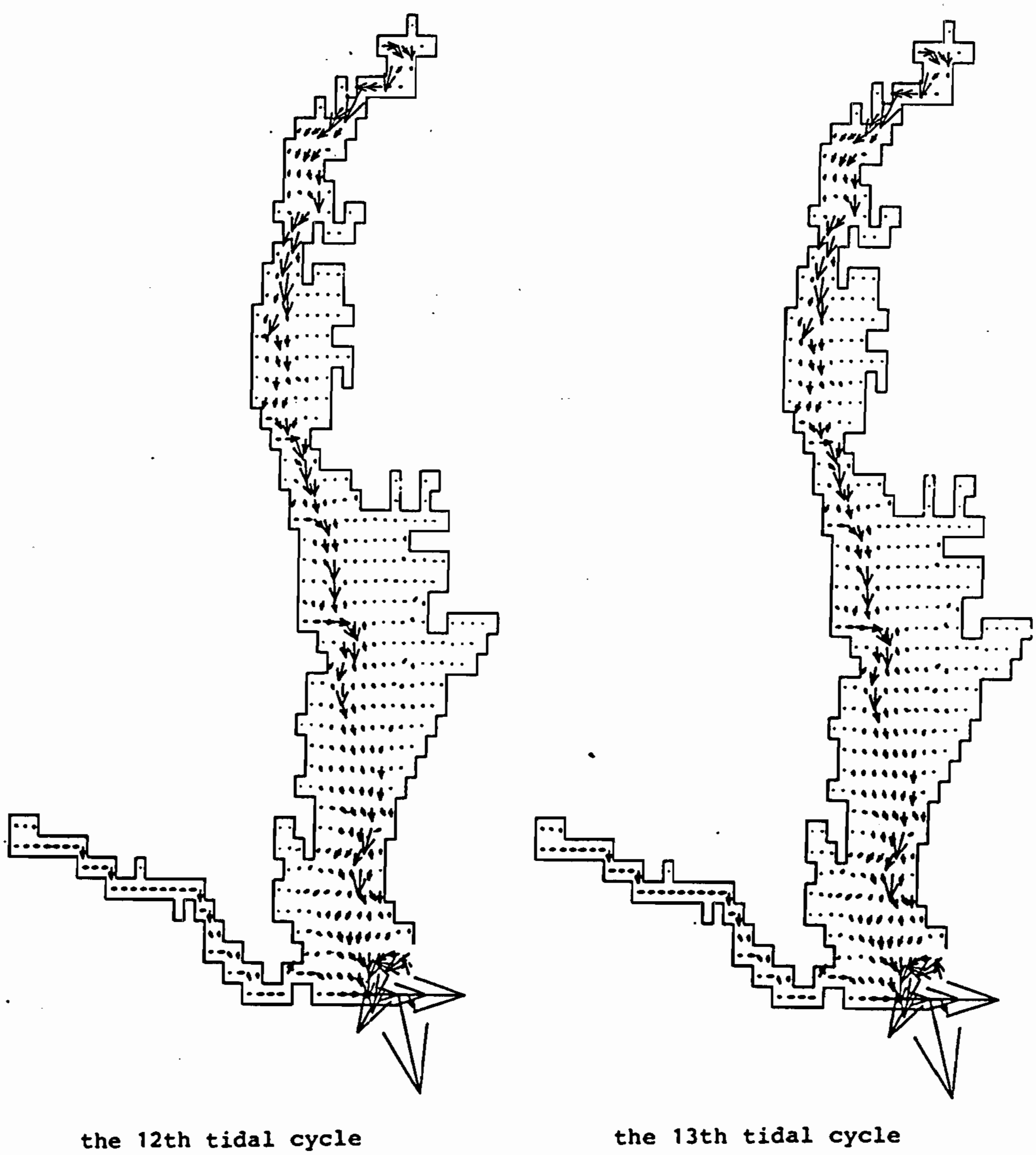


FIGURE 13. Simulated Tidally Averaged Volume Transport Vectors

4. PHOSPHORUS MODELING FOR THE BAY

A water quality simulation model which interfaces with the hydrodynamic model was developed for the prediction of water quality constituents. In this study, the depth-averaged two-dimensional mass transport equation is :

$$\frac{\partial \phi h}{\partial t}+\frac{\partial u \phi h}{\partial x}+\frac{\partial v \phi h}{\partial y}=\frac{\partial}{\partial x}(\Gamma_x \frac{\partial \phi h}{\partial x})+\frac{\partial}{\partial y}(\Gamma_y \frac{\partial \phi h}{\partial y}) \pm S \qquad (27)$$

where

ϕ = water quality constituent concentration.

h = water depth.

t = time.

u,v = velocity components in the x- and y- directions, respectively.

x,y = two-dimensional cartesian coordinate directions.

Γ_x , Γ_y = dispersion coefficients in the x- and y- directions, respectively.

S = source and sink terms of the constituent.

Numerical finite difference schemes are needed to obtain the solution of Eq. 27. It is known that low-order spatial or temporal discretization techniques results in significant numerical dispersion and parasitic oscillations in real time computations. They are not suitable for this study. Instead, a higher order scheme was used for solving this equation.

4.1 Two-Dimensional QUICKEST Method

The QUICKEST (Quadratic Upstream Interpolation for Convective Kinematics with Estimated Streaming Terms) technique was first proposed by Leonard (1979). The algorithm of QUICKEST is based on a conservative control-volume formulation with cell wall values of each field variable written in terms of a quadratic interpolation in any one coordinate axis the adjacent nodal values together with the values at the next upstream node. Leonard's QUICKEST is specifically designed to address unidirectional transient transport problems. Recently, Davis and Moore (1982) presented a two-dimensional version of the QUICKEST scheme. In this study, the formulation of the two-dimensional QUICKEST scheme is adopted from Hall and Chapman (1985).

The depth-averaged mass transport equation presenting here is for non-conservative substances with source and sink terms.

$$\frac{\partial \Phi}{\partial t}+\frac{\partial u\Phi}{\partial x}+\frac{\partial v\Phi}{\partial y}=\frac{\partial}{\partial x}(\Gamma_x\frac{\partial \Phi}{\partial x})+\frac{\partial}{\partial y}(\Gamma_y\frac{\partial \Phi}{\partial y})-K\Phi \tag{28}$$

where

$\Phi = \phi h$

K = decay coefficient for the constituent.

The computational grids and definitions of variables (u,v,h) are the same as those of the hydrodynamic model. D in the hydrodynamic model is the same definition and location as h in the QUICKEST. And Φ is the same location as h in the mass transport model as Figure 14 shows. In addition, Γ_x and Γ_y are defined on the same location as u and v, respectively. It's noted that the nodal values represent cell averages, and that cell wall values represent cell wall averages. The deviation of QUICKEST is based on the conservative control cell formulation and uses a spatial six-point upstream weighted interpolation surface with temporal advective correction to obtain a third-order approximation to cell- to-cell face average quantities. The QUICKEST formulation is therefore written

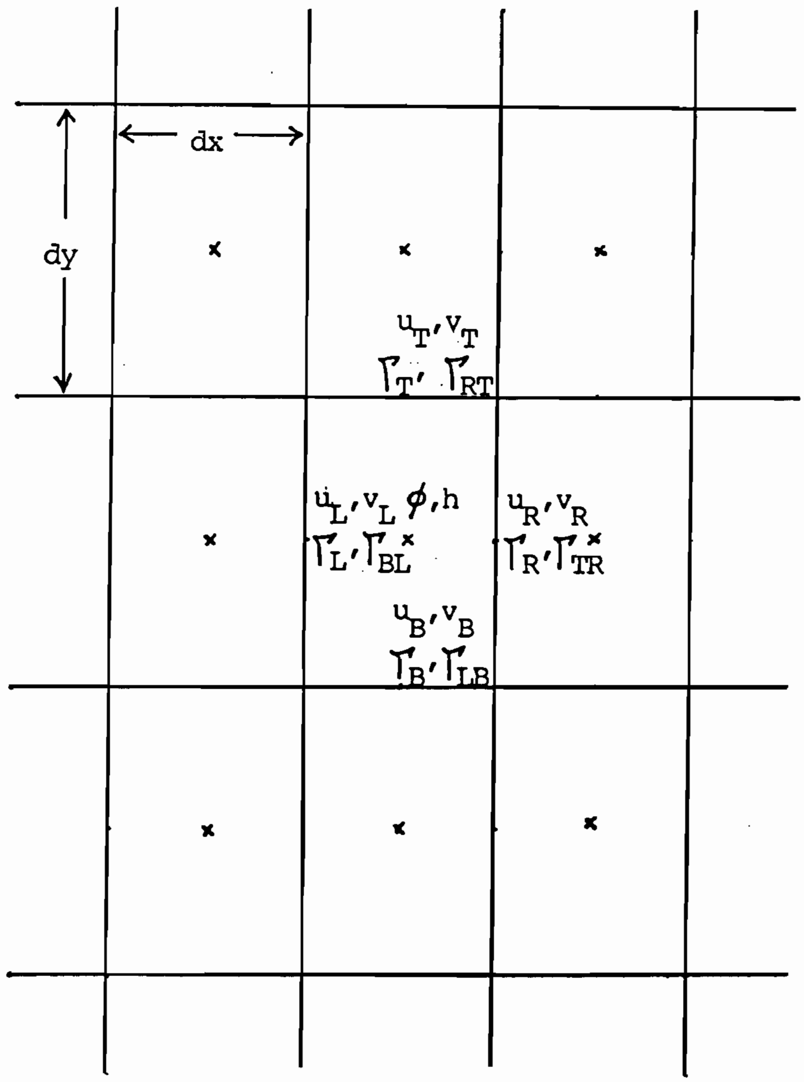


FIGURE 14. Computational Grids And Definition of Variable for QUICKEST Method

$$\Phi_{i,j}^{n+1} = \Phi_{i,j}^{n}\,(1-Kdt\,) - FR + FL - FT + FB \qquad (29)$$

where FR, FL, FT and FB represent advective and diffusive contributions through the right, left, top and bottom cell faces, respectively. Eq. 29 is actually an explicit finite difference scheme. If the u and v velocity components are assumed to be positive :

$$\begin{aligned} FR = C_R[\frac{1}{2}(\Phi_{i,j}^{n} + \Phi_{i+1,j}^{n}) - \frac{C_R}{2}\Delta_x\Phi_{i,j}^{n} + (\frac{\alpha_R}{2} - \frac{1}{6}(1-C_R^2))\,\delta_x^2\Phi_{i,j}^{n} \\ - \frac{C_{TR}}{2}\Delta_y\Phi_{i,j-1}^{n} + (\frac{\alpha_{TR}}{2} + \frac{C_{TR}^2}{6})\,\delta_y^2\Phi_{i,j}^{n} + \frac{C_R C_{TR}}{3}\delta_{xy}^2\Phi_{i+1/2,j-1/2}^{n}] \\ - \alpha_R(\Delta_x\Phi_{i,j}^{n} - \frac{C_R}{2}\delta_x^2\Phi_{i,j}^{n} - \frac{C_{TR}}{2}\delta_{xy}^2\Phi_{i+1/2,j-1/2}^{n}) \end{aligned} \qquad (30)$$

$$\begin{aligned} FT = C_T[\frac{1}{2}(\Phi_{i,j}^{n} + \Phi_{i,j+1}^{n}) - \frac{C_T}{2}\Delta_y\Phi_{i,j}^{n} + (\frac{\alpha_T}{2} - \frac{1}{6}(1-C_T^2))\,\delta_y^2\Phi_{i,j}^{n} \\ - \frac{C_{RT}}{2}\Delta_x\Phi_{i-1,j}^{n} + (\frac{\alpha_{RT}}{2} + \frac{C_{RT}^2}{6})\delta_x^2\Phi_{i,j}^{n} + \frac{C_T C_{RT}}{3}\delta_{xy}^2\Phi_{i-1/2,j+1/2}^{n}] \\ - \alpha_T(\Delta_y\Phi_{i,j}^{n} - \frac{C_T}{2}\delta_y^2\Phi_{i,j}^{n} - \frac{C_{RT}}{2}\delta_{xy}^2\Phi_{i-1/2,j+1/2}^{n}) \end{aligned} \qquad (31)$$

$$\begin{aligned} FL = C_L[\frac{1}{2}(\Phi_{i,j}^{n} + \Phi_{i-1,j}^{n}) - \frac{C_L}{2}\Delta_x\Phi_{i-1,j}^{n} + (\frac{\alpha_L}{2} - \frac{1}{6}(1-C_L^2))\,\delta_x^2\Phi_{i-1,j}^{n} \\ - \frac{C_{BL}}{2}\Delta_y\Phi_{i-1,j-1}^{n} + (\frac{\alpha_{BL}}{2} + \frac{C_{BL}^2}{6})\delta_y^2\Phi_{i-1,j}^{n} + \frac{C_L C_{BL}}{3}\delta_{xy}^2\Phi_{i-1/2,j-1/2}^{n}] \\ - \alpha_L(\Delta_x\Phi_{i-1,j}^{n} - \frac{C_L}{2}\delta_x^2\Phi_{i-1,j}^{n} - \frac{C_{BL}}{2}\delta_{xy}^2\Phi_{i-1/2,j-1/2}^{n}) \end{aligned} \qquad (32)$$

$$\begin{aligned} FB = C_B[\frac{1}{2}(\Phi_{i,j}^{n} + \Phi_{i,j-1}^{n}) - \frac{C_B}{2}\Delta_y\Phi_{i,j-1}^{n} + (\frac{\alpha_B}{2} - \frac{1}{6}(1-C_B^2))\delta_y^2\Phi_{i,j-1}^{n} \\ - \frac{C_{LB}}{2}\Delta_x\Phi_{i-1,j-1}^{n} + (\frac{\alpha_{LB}}{2} + \frac{C_{LB}^2}{6})\delta_x^2\Phi_{i,j-1}^{n} + \frac{C_B C_{LB}}{3}\delta_{xy}^2\Phi_{i-1/2,j-1/2}^{n}] \\ - \alpha_B(\Delta_y\Phi_{i,j-1}^{n} - \frac{C_B}{2}\delta_y^2\Phi_{i,j-1}^{n} - \frac{C_{LB}}{2}\delta_{xy}^2\Phi_{i-1/2,j-1/2}^{n}) \end{aligned} \qquad (33)$$

where

$$C_R = \frac{u_R dt}{dx} \quad ; \quad C_{TR} = \frac{v_R dt}{dy}$$

$$\alpha_R = \frac{\Gamma_R dt}{dx^2} \quad ; \quad \alpha_{TR} = \frac{\Gamma_{TR} dt}{dy^2} \qquad \text{for FR}$$

$$C_T = \frac{v_T dt}{dy} \quad ; \quad C_{RT} = \frac{u_T dt}{dx}$$

$$\alpha_T = \frac{\Gamma_T dt}{dy^2} \quad ; \quad \alpha_{RT} = \frac{\Gamma_{RT} dt}{dx^2} \qquad \text{for FT}$$

$$C_L = \frac{u_L dt}{dx} \quad ; \quad C_{BL} = \frac{v_L dt}{dy}$$

$$\alpha_L = \frac{\Gamma_L dt}{dx^2} \quad ; \quad \alpha_{BL} = \frac{\Gamma_{BL} dt}{dy^2} \qquad \text{for FL}$$

$$C_B = \frac{v_B dt}{dy} \quad ; \quad C_{LB} = \frac{u_B dt}{dx}$$

$$\alpha_B = \frac{\Gamma_B dt}{dy^2} \quad ; \quad \alpha_{LB} = \frac{\Gamma_{LB} dt}{dx^2} \qquad \text{for FB}$$

Δ and δ are the symbols of the forward difference and the central difference, respectively. Because the velocity component v and parameter Γ_y on the north-south cell surface and the velocity component u and parameter Γ_x on the east- west cell surface are omitted in the grid system in study. C_{TR} , α_{TR} , C_{RT} , α_{RT} , C_{BL} , α_{BL} , C_{LB} and α_{LB} are eliminated in Eqs. 30, 31, 32 and 33. These equations for the positive u and v are therefore simplified :

$$\begin{aligned} FR = C_R[\frac{1}{2}(\Phi^n_{i,j} + \Phi^n_{i+1,j}) - \frac{C_R}{2}\Delta_x\Phi^n_{i,j} + (\frac{\alpha_R}{2} - \frac{1}{6}(1 - C_R^2))\,\delta_x^2\Phi^n_{i,j}] \\ - \alpha_R(\Delta_x\Phi^n_{i,j} - \frac{C_R}{2}\delta_x^2\Phi^n_{i,j}) \end{aligned} \tag{34}$$

$$FT = C_T[\frac{1}{2}(\Phi^n_{i,j} + \Phi^n_{i,j+1}) - \frac{C_T}{2}\Delta_y\Phi^n_{i,j} + (\frac{\alpha_T}{2} - \frac{1}{6}(1 - C_T^2))\,\delta_y^2\Phi^n_{i,j}]$$
$$- \alpha_T(\Delta_y\Phi^n_{i,j} - \frac{C_T}{2}\delta_y^2\Phi^n_{i,j}) \tag{35}$$

$$FL = C_L[\frac{1}{2}(\Phi^n_{i,j} + \Phi^n_{i-1,j}) - \frac{C_L}{2}\Delta_x\Phi^n_{i-1,j} + (\frac{\alpha_L}{2} - \frac{1}{6}(1 - C_L^2))\,\delta_x^2\Phi^n_{i-1,j}]$$
$$- \alpha_L(\Delta_x\Phi^n_{i-1,j} - \frac{C_L}{2}\delta_x^2\Phi^n_{i-1,j}) \tag{36}$$

$$FB = C_B[\frac{1}{2}(\Phi^n_{i,j} + \Phi^n_{i,j-1}) - \frac{C_B}{2}\Delta_y\Phi^n_{i,j-1} + (\frac{\alpha_B}{2} - \frac{1}{6}(1 - C_B^2))\,\delta_y^2\Phi^n_{i,j-1}]$$
$$- \alpha_B(\Delta_y\Phi^n_{i,j-1} - \frac{C_B}{2}\delta_y^2\Phi^n_{i,j-1}) \tag{37}$$

where

for FR : $$\Delta_x\Phi^n_{i,j} = \Phi^n_{i+1,j} - \Phi^n_{i,j} \tag{38}$$

$$\delta_x^2\Phi^n_{i,j} = \Phi^n_{i+1,j} - 2\Phi^n_{i,j} + \Phi^n_{i-1,j} \tag{39}$$

for FT : $$\Delta_y\Phi^n_{i,j} = \Phi^n_{i,j+1} - \Phi^n_{i,j} \tag{40}$$

$$\delta_y^2\Phi^n_{i,j} = \Phi^n_{i,j+1} - 2\Phi^n_{i,j} + \Phi^n_{i,j-1} \tag{41}$$

for FL : $$\Delta_x\Phi^n_{i-1,j} = \Phi^n_{i,j} - \Phi^n_{i-1,j} \tag{42}$$

$$\delta_x^2\Phi^n_{i-1,j} = \Phi^n_{i,j} - 2\Phi^n_{i-1,j} + \Phi^n_{i-2,j} \tag{43}$$

for FB : $$\Delta_y\Phi^n_{i,j-1} = \Phi^n_{i,j} - \Phi^n_{i,j-1} \tag{44}$$

$$\delta_y^2\Phi^n_{i,j-1} = \Phi^n_{i,j}\ 2\Phi^n_{i,j-1} + \Phi^n_{i,j-2} \tag{45}$$

If the u and v velocity components are negative, the four dominated terms should be modified

$$FR = C_R\left[\frac{1}{2}(\Phi^n_{i,j} + \Phi^n_{i+1,j}) - \frac{C_R}{2}\Delta_x\Phi^n_{i,j} + \left(\frac{\alpha_R}{2} - \frac{1}{6}(1 - C_R^2)\right)\delta_x^2\Phi^n_{i+1,j}\right] - \alpha_R\left(\Delta_x\Phi^n_{i,j} - \frac{C_R}{2}\delta_x^2\Phi^n_{i+1,j}\right) \quad (46)$$

$$FT = C_T\left[\frac{1}{2}(\Phi^n_{i,j} + \Phi^n_{i,j+1}) - \frac{C_T}{2}\Delta_y\Phi^n_{i,j} + \left(\frac{\alpha_T}{2} - \frac{1}{6}(1 - C_T^2)\right)\delta_y^2\Phi^n_{i,j+1}\right] - \alpha_T\left(\Delta_y\Phi^n_{i,j} - \frac{C_T}{2}\delta_y^2\Phi^n_{i,j+1}\right) \quad (47)$$

$$FL = C_L\left[\frac{1}{2}(\Phi^n_{i,j} + \Phi^n_{i-1,j}) - \frac{C_L}{2}\Delta_x\Phi^n_{i-1,j} + \left(\frac{\alpha_L}{2} - \frac{1}{6}(1 - C_L^2)\right)\delta_x^2\Phi^n_{i,j}\right] - \alpha_L\left(\Delta_x\Phi^n_{i-1,j} - \frac{C_L}{2}\delta_x^2\Phi^n_{i,j}\right) \quad (48)$$

$$FB = C_B\left[\frac{1}{2}(\Phi^n_{i,j} + \Phi^n_{i,j-1}) - \frac{C_B}{2}\Delta_y\Phi^n_{i,j-1} + \left(\frac{\alpha_B}{2} - \frac{1}{6}(1 - C_B^2)\right)\delta_y^2\Phi^n_{i,j}\right] - \alpha_B\left(\Delta_y\Phi^n_{i,j-1} - \frac{C_B}{2}\delta_y^2\Phi^n_{i,j}\right) \quad (49)$$

where

for FR : EQ. 38

$$\delta_x^2\Phi^n_{i+1,j} = \Phi^n_{i+2,j} - 2\Phi^n_{i+1,j} + \Phi^n_{i,j} \quad (50)$$

for FT : EQ. 40

$$\delta_y^2\Phi^n_{i,j} = \Phi^n_{i,j+1} - 2\Phi^n_{i,j} + \Phi^n_{i,j-1} \quad (51)$$

for FL : EQ. 42

$$\delta_x^2\Phi^n_{i,j} = \Phi^n_{i+1,j} - 2\Phi^n_{i,j} + \Phi^n_{i-1,j} \quad (52)$$

for FB : EQ. 44

$$\delta_y^2\Phi^n_{i,j} = \Phi^n_{i,j+1} - 2\Phi^n_{i,j} + \Phi^n_{i,j-1} \quad (53)$$

The dispersion coefficients are constants for all cells with respect to the x- and y- directions in the model, therefore

$$\Gamma_R = \Gamma_L = \Gamma_x \tag{54}$$

$$\Gamma_T = \Gamma_B = \Gamma_y \tag{55}$$

that is,

$$\alpha_R = \alpha_L = \alpha_x \tag{56}$$

$$\alpha_T = \alpha_B = \alpha_y \tag{57}$$

With examining the sign of C value for each face in a cell, one can determine which formulas (Eqs. 34, 35, 36, 37, 46, 47, 48 and 49) should be used with Eq. 29. Figure 15 presents the grid points required for each quadratic interpolation surface. It is assumed that the velocity components do not change signs in one cell. The time step used in this model is 60 sec, which is small enough to minimize the numerical dispersion problem. The time step is the same as that used in the circulation model so that the two models can be integrated easily. In addition, the cell size is the same as the design of the grid system for the circulation model. Dispersion coefficients Γ_x and Γ_y of 645 ft^2 /sec and a decay coefficient K of 0.1 day^{-1} are used in the phosphorus calculation.

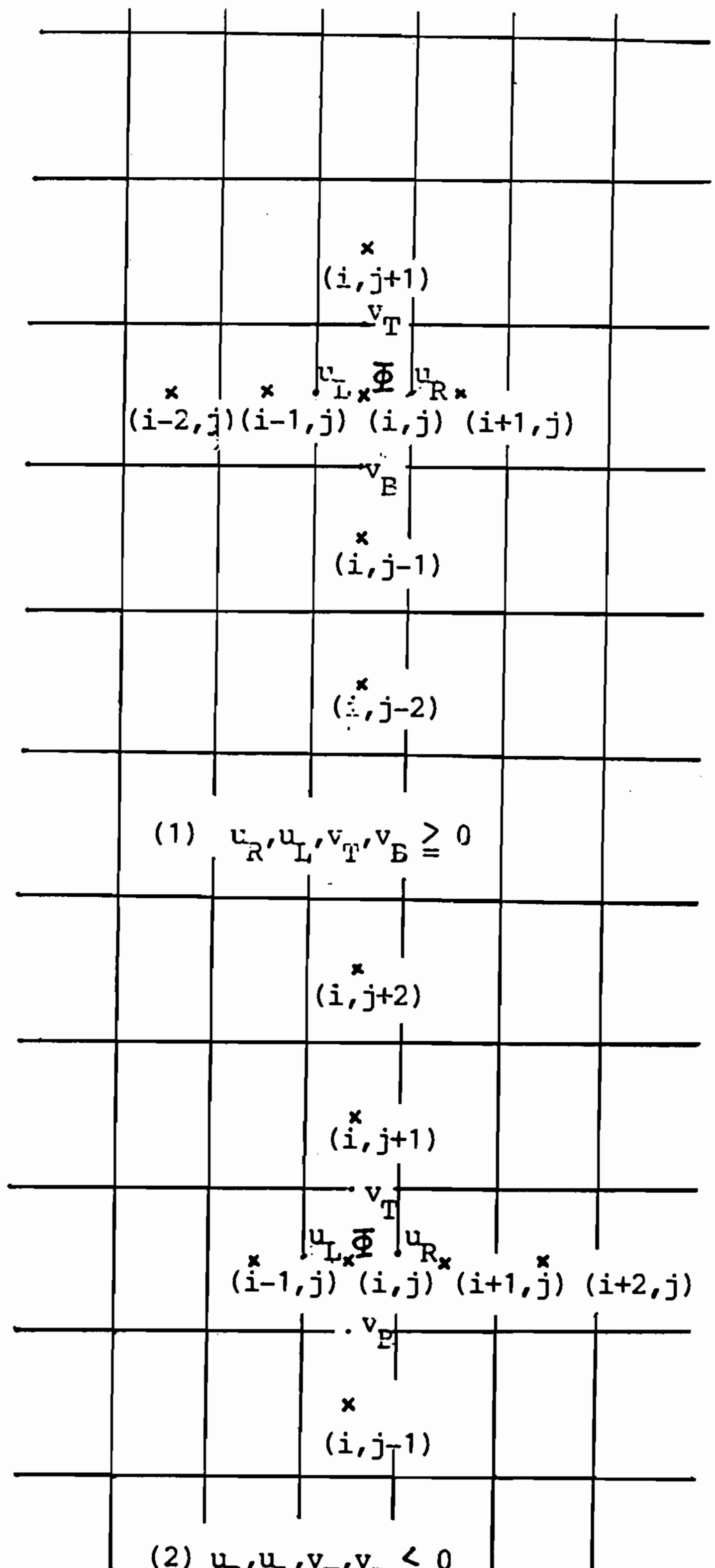


FIGURE 15. Grid Points Necessary for Each Quadratic Interpolation

Surfaces in the 2-D QUICKEST Computational Lattice

4.2 Application to the Chesapeake Bay

The phosphorus concentration is computed at the center of a grid. The total phosphorus boundary condition applied at the mouth of the Bay is 0.1 mg/L ; 0.2 mg/L at the fresh water inflows from the Susquehanna River, Potomac River and Rappahannock River. The simulation region is only up to the junction of the Appomattox River and the James River in the grid system. The James River from Richmond to Hopewell is not explicitly included in the model because this reach is much narrower than the grid size. Instead, the phosphorus loads from this section of the river are lumped into one input in the Hopewell area as a boundary condition for the model. The phosphorus concentration at the head of James River is 0.3 mg/L associated with a freshwater flow of 2300 cfs in Richmond (Lung,1987). The initial concentrations for phosphorus are zeros in each grid except those in the open boundaries. Because there is no normal velocity component along the coast, the phosphorus concentration distributed by that cell face will be very small from Eqs. 34 to 53. Further, in light of the flow direction, the concentration just outside of the boundary is assumed to be the same value as that of the adjacent interior grid.

The sequence of computation is, firstly, to solve for the volume transport components (uD, vD); secondly, to solve for the water surface elevation (η) and finally to calculate the depth-averaged concentration (Φ). The flow chart for programming the hydrodynamic and phosphorus transport models are shown in Figure 16.

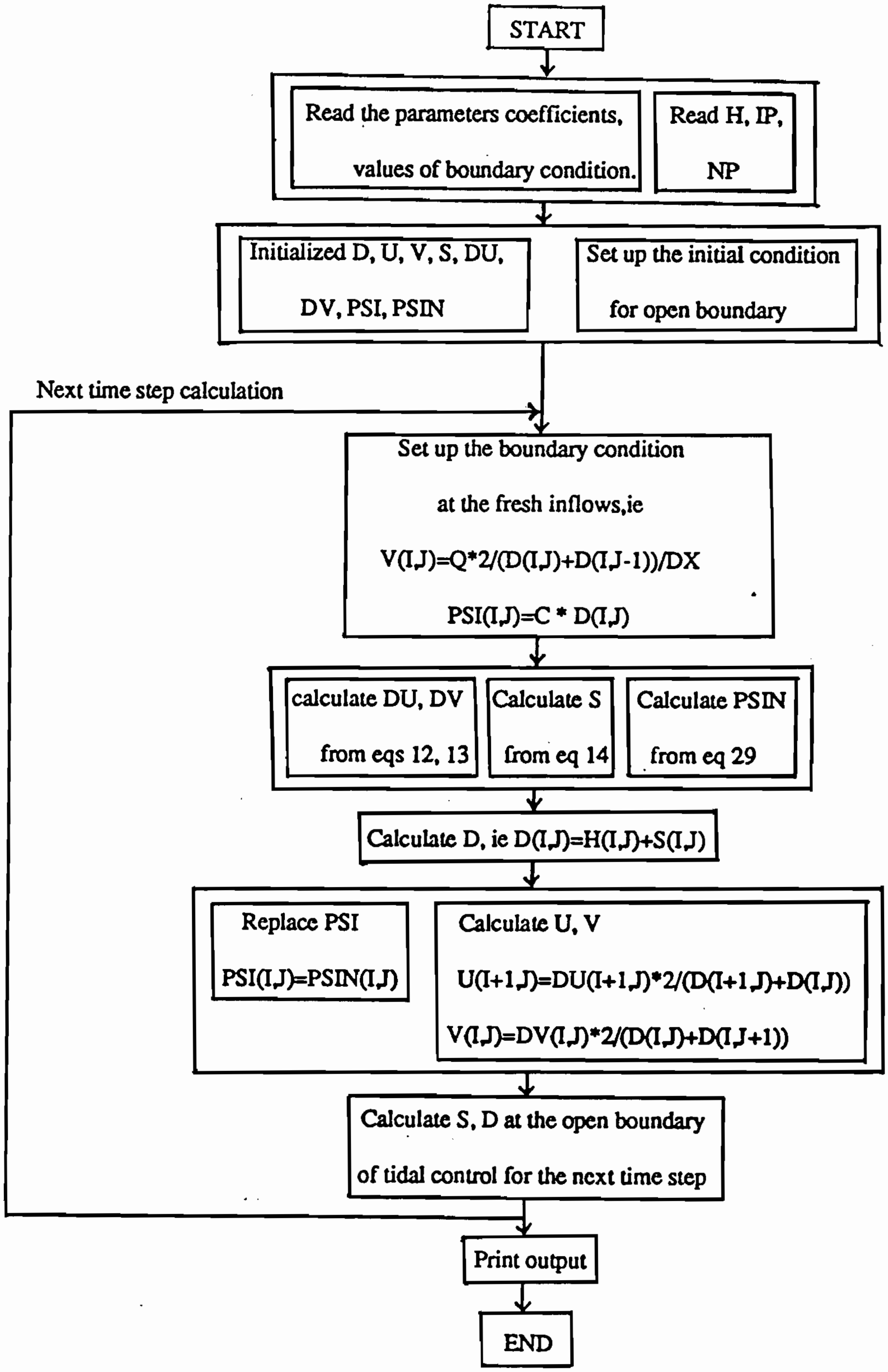


FIGURE 16. Flow Chart of Programming

4.3 Model Results

The model was first checked for mass conservation. The phosphorus concentration for the boundary condition is replaced by the mass loading. This modification, however, is the easiest way to test the mass balance of the substance. The boundary conditions for this test are James River inflow 3.0E6 cfs and the waste loading input ww (= 3.0E10 lb/day) for a conservative substance. And the tidal control is at the mouth of the Bay. The loading input, which has to be converted to be depth-averaged concentration, is put at one selected grid point of the James River system. The incremental depth-averaged concentration for each time step at the waste input grid is

$$DS = ww \cdot dt / 86400. / dx / dy / 5.4 \tag{58}$$

Table 3 presents the comparison of mass conservative tests The third column of Table 3 is the mass input,

$$mass\ input = ww \cdot dt / 86400. \cdot NTIME \tag{59}$$

where NTIME is the number of time step. The fourth column is the mass remaining in the boundary,

$$mass = \Phi(I,J) \cdot dx \cdot dy \cdot 5.4 \tag{60}$$

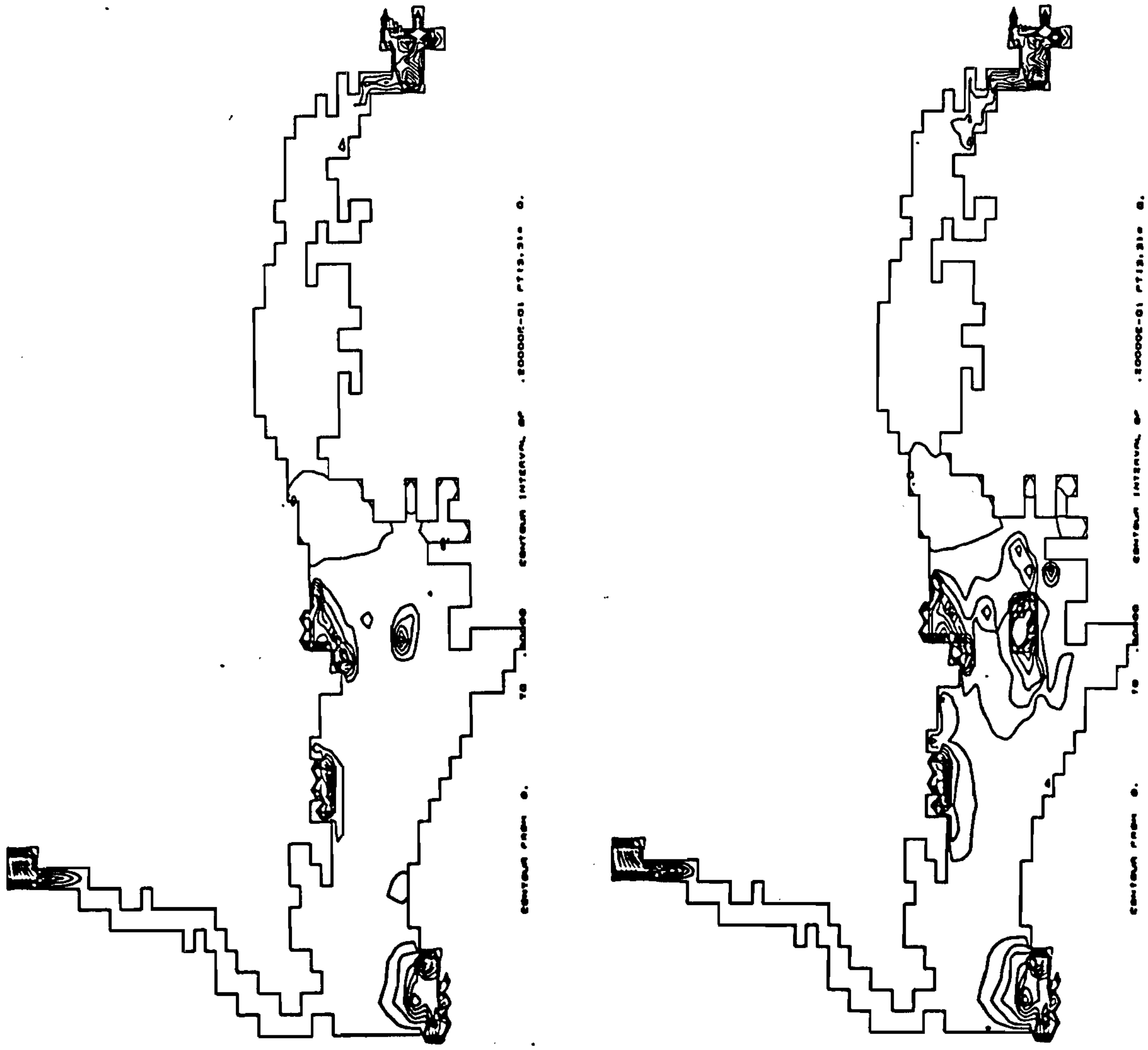
where Φ (I,J) is the depth-averaged concentration in a grid point (I,J). Furthermore, since the number of the time step for these tests is small enough, the substance mass will not flow into the Ocean. Table 3 shows that the errors for different locations of mass input are quite different. It is explained that the substance transport is restricted by the bathymetry, especially that of the James River; and that the assumption of the boundary condition along the coast is the error which comes from. Therefore, the errors of row 3 and 6 in Table 3 are less than the others.

Due to the low discharge flow at the upstream of the James River, the transport and dispersion of substance are very slow in the James River. The phosphorus dynamic model should have the simulated time of a long term period (ie. month or year). Besides, the hydrodynamic part reaches the dynamic steady-state condition after the downstream forcing function is repeated 13 times. Therefore, hydrodynamic model results following 13 tidal cycles are applied to the phosphorus dynamic part for the phosphorus simulation. Figure 17, 18, 19 present the model calculated concentration contours for the 1st, 2nd and 3rd month of simulation time. A comparison of the concentration distributions for the conservative and non-conservative constituent is also presented. In addition, the phosphorus concentration distribution in Figure 20 shows the phosphorus dynamics between the James River and the Chesapeake Bay.

g

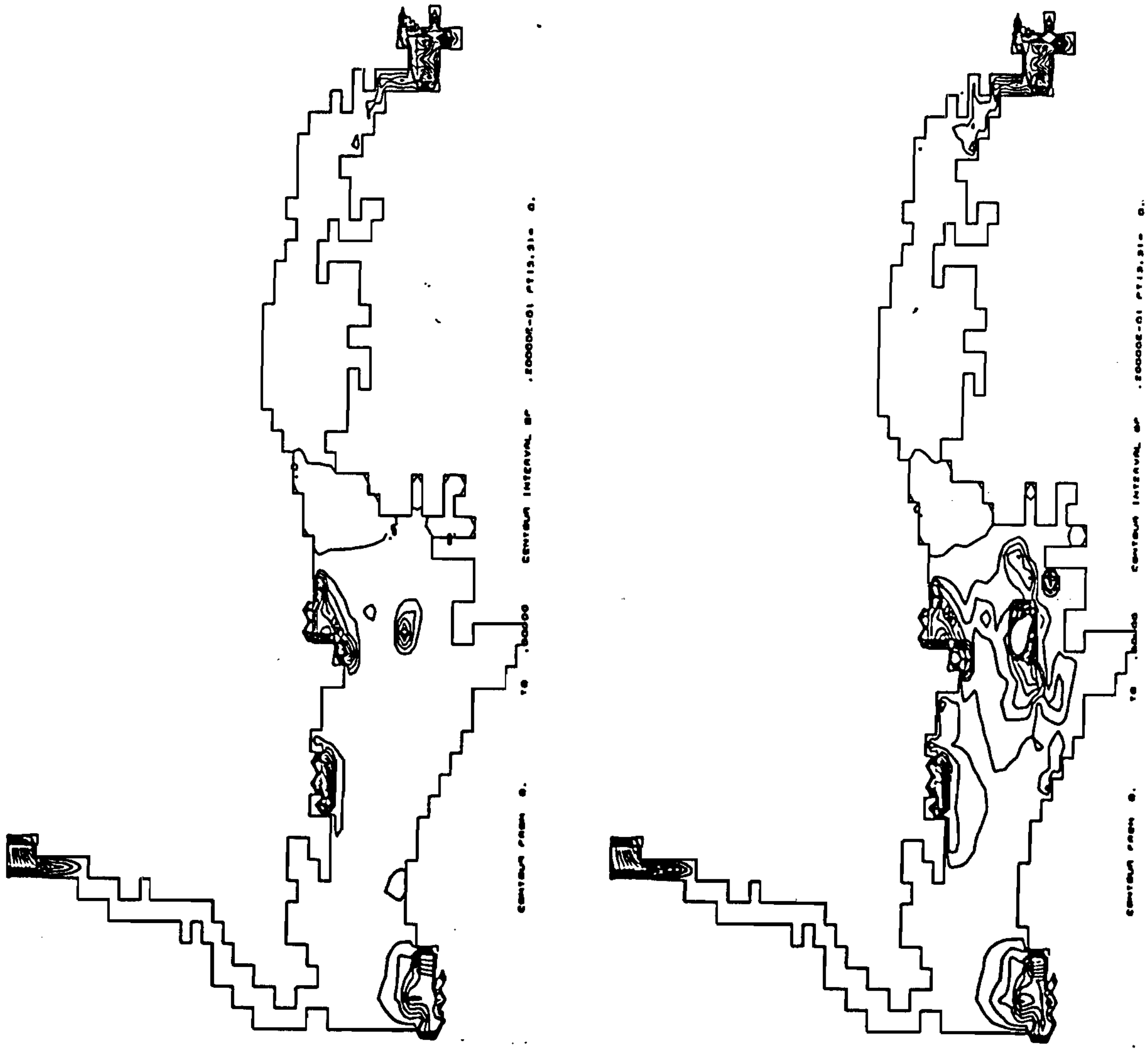
NUMBER OF TIME STEP	MASS INPUT NODE	WASTE MASS INPUT (lb)	MASS REMAINING IN DOMAIN (lb)	ERROR PERCENTAGE (%)
120	PSIJN(3,8)	25E8	2499691144	0.012
	PSIJN(15,6)		2472912240	-1.08
	PSIBN(13,16)		2500392730	0.016
360	PSIJN(3,8)	75E8	7478783832	-0.28
	PSIJN(15,6)		7268830599	-3.08
	PSIBN(13,16)		7500642213	-0.0086

TABLE 3. Mass Balance Test for the Water Quality Model



non-conservative conservative

FIGURE 17. Model Calculated Phosphorus Concentration Contours for the 1st Month



non-conservative conservative

FIGURE 18. Model Calculated Phosphorus Concentration Contours for the 2nd Month

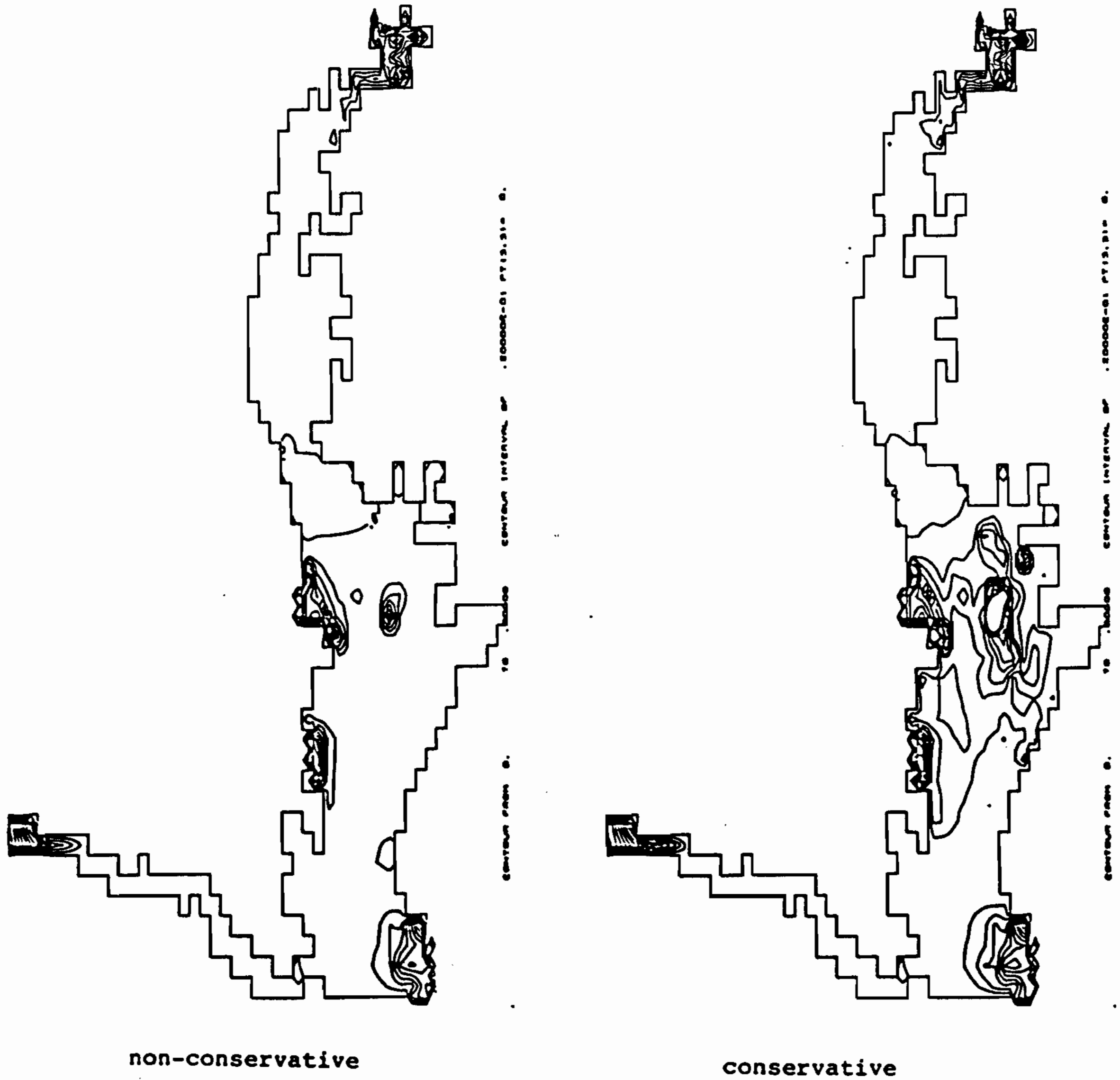


FIGURE 19. Model Calculated Phosphorus Concentration Contours for

the 3rd Month

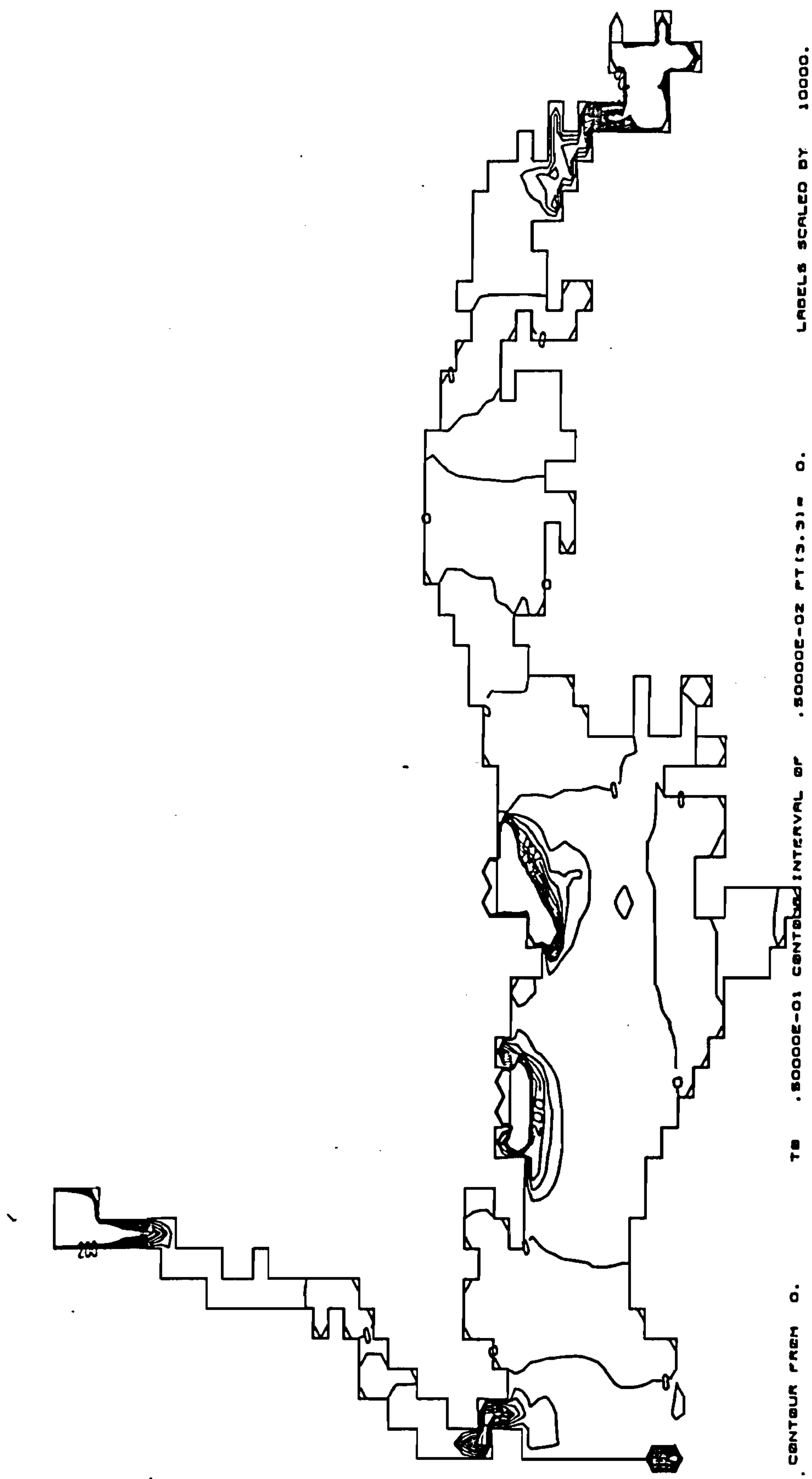


FIGURE 20. Numerical Simulated Result for the Phosphorus Dynamics Between

the James River And the Chesapeake Bay

5. SUMMARY AND CONCLUSION

A depth-averaged hydrodynamic model and a fate and transport model of phosphorus have been developed for the Chesapeake Bay. Conceptualization of the hydrodynamic model was derived from the work by Blumberg (1977). The QUICKEST scheme is utilized to solve the phosphorus transport equation. Both hydrodynamic and water quality models have been successfully tested to maintain mass conservation in real time. The model results show that the Bay system reaches a dynamic steady-state condition following constant forcing function at the mouth of the Bay. During one tidal cycle, currents reverse their direction due to the tidal elevation at the mouth.

The simulation results for the fate and transport of phosphorus show that the phosphorus loading from the upstream of the James River will not have an influence on the upper part of the Chesapeake Bay on a short time basis. Wastewater input in the upper James Estuary only contributes to local increases of phosphorus concentrations. Once it enters the Bay, phosphorus would be transported toward the Atlantic Ocean along the current flow and diluted with the large volume of water in the Ocean. Figure 18, 19 and 20 show that there is no much progress for the phosphorus transport along the James River when the simulation time extends to 3 months, even though the constituent is assumed to be conservative. The explanation is that the low discharge flow from the upper James River can not steer the phosphorus transport as fast as possible; and that the bathymetry of the James River makes some restrictions for the phosphorus transport. Besides, the phosphorus transport for the lower Chesapeake part reveals that it is under the tidal control.

For the first few time steps the model calculated concentrations with QUICKEST are very small negative values if the initial concentrations are zeros. It is possible to produce little error when doing the test of mass balance for constituent in a control volume. On the other hand, it is seen that from Table 3 the loading input at the most interior grid point (column 3 and 6) gave the most accurate result for mass conservation because this grid point is not close to the coast and the phosphorus calculation is not much related to the coastal boundary.

For the requirement of stability criteria, the time step in the hydrodynamic model could be much smaller than that of the transport model. However, the same time step is applied to these two models. It arises the problem that quite a lot of simulation time has to be taken for generating the concentration distribution of a long-term simulation result.

APPENDIX 1

```
  9   48    9758  2.5E-3  9.0E-5   0.0  5.91  6.60  32.2  0.1
 60 9986.67 20597.5 8.21E4  3.11E4 2.96E4 1.64E4 645.  645.
 0.2 0.2 0.3 0.2 0.1
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 12.5 14.3
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 14.8 13.0 12.5 14.3
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 15 15 14.8 13 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 16.2 15 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 17.3 0 12.3 14.5 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 17.8 19.3 18.3 10 20 12.1 14.6 17.3 14.6 12.3 0 0 0 0 0 0
0 0 0 0 0 0 0 0  29.4 14.5 25  17.8 0 0 10 0 0 0 0 0 0 0 0 0 0 0 0
7  7 7.5 8 8.5 14.5 12.5 16.3 29.4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
7 7 7.5 8 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 23 21 21 20 11  8  1  1
 0  2  4  2  2 10  4  8  3
 0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0 30 30 30  0  0  0  0  0  0  0
 0  3 12 42 24 24  0  0 18 21 21 23 27 39 42 66 66 18 30  0  0  0  0  0  0  0
15 24  3  0  0  6  6 18 60 18 21 21 24 33 48 24 23 24 30  0  0  0  0  0  0  0
 0  0  0  0  0  0  0  6 18 21 27 30 40 36 36 22 18 20 30  0  0  0  0  0  0  0
 0  0  0  0  0  0  2  6 21 27 36 42 30 30 18 20  3  3  0  0  0  0  0  0  0  0
 0  0  0  0 18  6  3 18 36 33 33 30 33 30 30 30  0  0  0  0  0  0  0  0  0  0
 0  0  0  0  6 18 40 18 30 30 33 36 42 42 30  0  0  0  0  0  0  0  0  0  0  0
 0  0  0  0  0  6 18 21 24 24 40 39 78 36 12  0  0  0  0  0  0  0  0  0  0  0
 0  0  0  0 15 18  3  0 15 30 42 36 48 54 36  0  0  0  0  0  0  0  0  0  0  0
 0  0  0  0  1  1  0  0  6 12 24 37 40 60 40 18  0  0  0  0  0  0  0  0  0  0
 0  0  0  0  0  0  0  0  6 18 32 36 40 60 48 30  0  0  0  0  0  0  0  0  0  0
 0  0  0  0  0  0 18  3 21 27 33 36 39 42 60 33  9  0  0  0  0  0  0  0  0  0
 0  0  0  0  0  0  6  6 29 30 36 38 40 41 54 39 21  2  0  0  0  0  0  0  0  0
 0  0  0  0  0  0  6  6 18 30 41 48 40 40 48 32 30 18  3  0  0  0  0  0  0  0
 0  0  0  0  0  0  6 24 36 39 48 48 38 34 36 53 30 21  9  6  0  0  0  0  0  0
 0  0  0  0  0  0  0 12 15 48 78 42 28 26 36 36 42 54 24 18  4  0  0  0  0  0
 0  0  0  0  0  0  0  2 18 41 102 30 31 24 17 15 78 18  9 13 15  0  0  0  0  0
 0  0  0  0  0  0  0  0  0 33 66 66 36 30 18  9  6 64 10  6 15 16 12  9  0  0
 0  0  0  0  0  0  0  0  1  9 54 72 36 21  9  4 12 54 12  4  9 15  4  4  3  0
 0  0  0  0  0 48 48 24 32 44 66 48 30 15  0  1 12 66 12  0  0  3  9  7  4  2
 0  0  0  0  0 48 48 38 39 60 36 16 30 18  2  0  3 12 54  0  0  0  0  0  0  0
 0  0  0  0  0  0  6 30 42 84 22 21 18 16 15  6 30 15 18  2  6  0  0  0  0  0
 0  0  0  0  0  0 15 30 48 92 24 24 12  6  3  1 42  0  6  9  1  0  0  0  0  0
 0  0  0  0  0  0 15 42 42 54 39 27 21  1  0  3 48  0  0  0  0  0  0  0  0  0
 0  0  0  0  0 32 36 48 78 22 17 10  6 18  1  9 12  6  6  6  2  0  0  0  0  0
 0  0  0  0  0 28 48 66 24  6  0 30  0  0  0 18  0  0  4  0  0  0  0  0  0  0
 0  0  0  0 18 30 54 42  6  0  5  0  0  0  0  3  0  0  3  6  0  0  0  0  0  0
 0  0  0  0  0 48 102 15  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0  0  0 36 48 90 18  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0  0 33 40 66 18  3  6  6  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0  6 33 66 36 24 24  6  2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0  3 33 48 54 20 30 20  6  0  6  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0 24 33 42 54 18  3 12 18 18  6  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0  6 35 54 42 18  1 12  6  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0 18 30 54 18 18 12  1  1  0 12  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0  0 12 36 78  6 42 18  0 30  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0  0 12 20 54 18  0 12 26 24  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
 0  0  0 12 48 24  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

0	0	0	0	3	60	18	0	27	36	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	13	16	30	42	24	30	0	24	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	16	21	24	36	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	18	18	21	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	3	12	16	16	18	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	6	12	12	9	18	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	8	0	12	18	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	6	12	12	24	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	12	18	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	12	0	6	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	5	7	6	4	4	5	8	8	8	6	7	7	6	7	7	9	8	6	6	6	6	6	5	5	4
4	3	2	1	1	1	1	1	2	2	3	4	3	4	4	4	5	9	11	14	13	16	10	13	11	12
12	11	10	7	8	8	11	11	12	14	14	14	15	17	13	13	15	15	11	16	7	7	4	4	7	8
8	10	8	10	8	4	3	3	6	5	4	6	6	3	6	3	6	1								

APPENDIX 2

```
      PROGRAM ESTUARY(INPUT,OUTPUT,IN5,TAPE2=OUTPUT,
     *          TAPE5=IN5,TAPE7,TAPE6)
C**********************************************************************C
C     THE PROGRAM IS A SIMULATION MODEL FOR HYDRODYNAMICS OF CURRENT   C
C     FLOW AND TRANSPORT-DISPERSION OF PHOSPHROUS APPLIED TO THE       C
C     CHESAPEAKE BAY AND JAMES RIVER REGION. ALSO, THE PROGRAM OUTPUTS C
C     THE VELOCITY VECTORS, AVERAGED VOLUME TRANSPORT VECTORS AND      C
C     PHOSPHORUS CONCENTRATION FOR EACH GRID POINTS FOR GRAPHING.      C
C**********************************************************************C
      DIMENSION DJAM(0:26,0:10),UJAM(0:26,0:10),VJAM(26,0:10),
     *          SJAM(0:26,0:10),DUJAM(26,10),DVJAM(26,10),
     *          HJAM(0:26,0:10),DB(0:26,0:50),UB(0:26,0:50),
     *          VB(26,0:50),SB(0:26,0:50),DUB(26,50),DVB(26,50),
     *          HB(0:26,0:50),Q(4),IPJ(10),NPJ(10),IPB(50),NPB(50),
     *          SHUPJAM(26,10),SHUJAM(26,10),DUPPJAM(26,10),
     *          SHVPJAM(26,10),SHVJAM(26,10),DVPPJAM(26,10),
     *          DUPJAM(26,10),DVPJAM(26,10),C(4),
     *          SHUPB(26,50),SHUB(26,50),DUPPB(26,50),DUPB(26,50),
     *          SHVPB(26,50),SHVB(26,50),DVPPB(26,50),DVPB(26,50),
     *          SPPJAM(26,10),SPJAM(26,10),SPPB(26,50),SPB(26,50),
     *          AUJAM(26,10),AVJAM(26,10),AUB(26,50),AVB(26,50),
     *          PSIJ(-1:27,-1:11),PSIB(-1:27,-1:50),PSIJN(25,9),
     *          PSIBN(25,48),APJAM(26,10),APB(26,48),CONJ(26,10),
     *          CONB(26,48)
C
      INTEGER TIME
      REAL K,LEAP,KK
      COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
      COMMON/MASS/ ARFAX,ARFAY
      COMMON/AVERAGE/ AUJAM,AVJAM,AUB,AVB,APJAM,APB
      COMMON/AVE1/   DUJAM,DVJAM,DUB,DVB,PSIJ,PSIB
      DATA NT1,NT2 /8257,9007/
C*********************************************************************
C   PARAMETERS AND BOUNDARY VALUES INPUT
C*********************************************************************
      READ (5,*) MAXJ,MAXB,NTIME,K,F,W,T1,T2,G,KK
      READ (5,*) DT,DX,DY,(Q(I),I=1,4),DIFX,DIFY,
     *           (C(I),I=1,4),CO
C ***** DIFFUSION COEFFICIENT ****************************************
      ARFAX= DIFX * DT / DX**2
      ARFAY= DIFY * DT / DY**2
C ***** THE NUMBER OF TIME STEP FOR THE 1ST AND 2ND AVERAGED *****
C ***** VOLUME TRANSPORT DURING TWO TIDAL CYCLES             *****
      NNT1=NT2-NT1
      NNT2=NTIME-NT2
C
      MAXJJ=MAXJ+1
      MAXBB=MAXB+1
      NJ = 26
      MJ = MAXJ + 2
      NB = 27
      MB = MAXB + 2
C*********************************************************************
C   THE INITIAL WATER ELEVATION AND THE GRID SEARCH ARRAYS INPUT
C*********************************************************************
      READ (5,*) ((HJAM(I,J),I=0,26),J=1,MAXJJ)
      READ (5,*) (IPJ(J),J=1,MAXJ),(NPJ(J),J=1,MAXJ)
```

```
      READ (5,*) ((HB(I,J),I=0,25),J=0,MAXBB)
      READ (5,*) (IPB(J),J=1,MAXB),(NPB(J),J=1,MAXB)
C ***** SET UP THE INITIAL VALUES FOR EACH VARIABLES **************
      DO 19 J=0,MAXBB
19       HB(26,J)=0.0
      CALL INIT(MAXJJ,DJAM,UJAM,VJAM,HJAM,SJAM,DUJAM,DVJAM)
      CALL INIT(MAXBB,DB,UB,VB,HB,SB,DUB,DVB)
      CALL INIT1(10,AUJAM,AVJAM,APJAM)
      CALL INIT1(50,AUB,AVB,APB)
      DO 137 J=-1,MB
        DO 137 I=-1,NB
137       PSIB(I,J)=0.0
      DO 147 J=-1,MJ
        DO 147 I=-1,NJ
147       PSIJ(I,J)=0.0
      DO 157 J=1,48
         DO 157 I=1,26
            IF (J .LE. 10) CONJ(I,J)=.0
            CONB(I,J)=.0
157   CONTINUE
C*******************************************************************
C   THE INITIAL BOUNDARY VALUES OF WATER ELEATION AT THE MOUTH OF
C   CHESAPEAKE BAY
C*******************************************************************
      DO 99 I=16,18
         SB(I,0)=2.82
         DB(I,0)=HB(I,0)+SB(I,0)
99    CONTINUE
      DO 999 J=1,3
         SB(18,J)=2.82
         DB(18,J)=HB(18,J)+SB(18,J)
999   CONTINUE
C*******************************************************************
C   BEGIN THE SIMULATION AND MARCH THE TIME STEP
C*******************************************************************
      RTIME=0.0
      DO 777 TIME=1,NTIME
         RTIME=DT*TIME/60./60.
C ***** TRANSFER THE BOUNDARY VALUES FROM DISCHARGE TO               *
C ***** HORIZONTAL OR VERTICAL VELOCITY FOR THE HYDRODYNAMIC PART*
         VB(13,48)=-1*Q(1)*2./(DB(13,48)+DB(13,47))/DX
         UB(6,19)=Q(2)*2./(DB(6,19)+DB(5,19))/(2.*DY)
         UB(6,20)=UB(6,19)
         UJAM(1,9)=Q(3)*2./(DJAM(0,9)+DJAM(1,9))/(2.*DY)
         UJAM(1,8)=UJAM(1,9)
         UB(7,12)=Q(4)*2./(DB(7,12)+DB(6,12))/(2.*DY)
         UB(7,13)=UB(7,12)
C ***** TRANSFER THE BOUNDARY VALUES FROM CONCENTRATION TO          *
C ***** DEPTH-AVERAGED CONCENTRATION  FOR THE TRANSPORT-            *
C ***** DISPERSION PART                                              *

         PSIB(13,48)=C(1)*DB(13,48)
         PSIB(13,49)=PSIB(13,48)
         PSIB(5,20)=C(2)*DB(5,20)
         PSIB(4,20)=PSIB(5,20)
         PSIB(5,19)=C(2)*DB(5,19)
         PSIB(4,19)=PSIB(5,19)
         PSIJ(0,9)=C(3)*DJAM(0,9)
         PSIJ(-1,9)=PSIJ(0,9)
         PSIJ(0,8)=C(3)*DJAM(0,8)
         PSIJ(-1,8)=PSIJ(0,8)
         PSIB(6,13)=C(4)*DB(6,13)
         PSIB(5,13)=PSIB(6,13)
         PSIB(6,12)=C(4)*DB(6,12)
         PSIB(5,12)=PSIB(6,12)
         DO 98 I=16,17
```

```
            PSIB(I,0)=CO*DB(I,0)
 98         PSIB(I,-1)=PSIB(I,0)
         DO 998 J=1,3
            PSIB(18,J)=CO*DB(18,J)
998         PSIB(19,J)=PSIB(18,J)
C ***** CALCULATE THE VOLUME TRANSPORT COMPONENTS ************************
C *********** JAMES RIVER PART ****************************************
         LEAP=1.0
         IF (TIME.EQ. 1) LEAP=2.0
         DO 100 J=1,MAXJ
            IF (IPJ(J) .NE. 0) THEN
               IF (J .EQ. 2) THEN
                  DJAM(25,2)=DB(1,2)
                  DJAM(26,2)=DB(2,2)
                  DJAM(25,1)=DB(1,1)
                  UJAM(26,2)=UB(2,2)
                  VJAM(25,2)=VB(1,2)
               END IF
               CALL DUTERM(IPJ,NPJ,J,DJAM,UJAM,VJAM,SJAM,DUJAM,
     *                  SHUPJAM,SHUJAM,DUPPJAM,DUPJAM,1,1)
               CALL DVTERM(IPJ,NPJ,J,DJAM,UJAM,VJAM,SJAM,DVJAM,
     *                  SHVPJAM,SHVJAM,DVPPJAM,DVPJAM,1,1)
               CALL JAMESV(J,DJAM,UJAM,VJAM,SJAM,DUJAM,DVJAM,
     *            SHUPJAM,SHUJAM,DUPPJAM,DUPJAM,SHVPJAM,SHVJAM,
     *            DVPPJAM,DVPJAM,1)
            END IF
100      CONTINUE
C ******** CHESAPEAKE BAY PART ***********************************
         DO 50 J=1,MAXB
            CALL DUTERM(IPB,NPB,J,DB,UB,VB,SB,DUB,
     *               SHUPB,SHUB,DUPPB,DUPB,1,2)
            CALL DVTERM(IPB,NPB,J,DB,UB,VB,SB,DVB,
     *               SHVPB,SHVB,DVPPB,DVPB,1,2)
            IF (J .EQ. 2) THEN
               UB(1,2)=UJAM(25,2)
               DB(0,2)=DJAM(24,2)
            END IF
            CALL BAYV(J,DB,UB,VB,SB,DUB,DVB,
     *         SHUPB,SHUB,DUPPB,DUPB,SHVPB,SHVB,DVPPB,DVPB,1)
 50      CONTINUE
C ***** CALCULATE THE CHANGE OF WATER ELEVATION ****************
C ******* THE JAMES RIVER PART **********************************
         DO 400 J=1,MAXJ
            IF (IPJ(J) .NE. 0) THEN
               IF (J.EQ. 2) DJAM(25,2)=DB(1,2)
               CALL STERM(IPJ,NPJ,J,DJAM,UJAM,VJAM,SJAM,HJAM,
     *               SPJAM,SPPJAM,PSIJ,PSIJN,1)
               CALL JAMESS(J,DJAM,UJAM,VJAM,SJAM,HJAM,
     *                 SPJAM,SPPJAM,PSIJ,PSIJN,1)
            END IF
400      CONTINUE
C ******** THE CHESAPEAKE BAY PART ********************************
         DO 350 J=1,MAXB
            CALL STERM(IPB,NPB,J,DB,UB,VB,SB,HB,SPB,SPPB,
     *               PSIB,PSIBN,1)
            IF (J .EQ. 2) DB(0,2)=DJAM(24,2)
            CALL BAYS(J,DB,UB,VB,SB,HB,SPB,SPPB,PSIB,PSIBN,1)
350      CONTINUE
C ***** CALCULATE THE DEPTH-AVERAGED CONCENTRATION **************
C ******** THE JAMES RIVER PART **********************************
         PSIJ(25,2)=PSIB(1,2)
         PSIJ(26,2)=PSIB(2,2)
         DO 500 J=1,MAXJ
            IF (IPJ(J) .NE. 0) THEN
               CALL STERM(IPJ,NPJ,J,DJAM,UJAM,VJAM,SJAM,HJAM,
     *                  SPJAM,SPPJAM,PSIJ,PSIJN,3)
```

```
                    CALL JAMESS(J,DJAM,UJAM,VJAM,SJAM,HJAM,
     *                          SPJAM,SPPJAM,PSIJ,PSIJN,3)
                 END IF
 500          CONTINUE
 C ******** THE CHESAPEAKE BAY PART *****************************
              PSIB(0,2)=PSIJ(24,2)
              PSIB(-1,2)=PSIJ(23,2)
              DO 550 J=1,MAXB
                 CALL STERM(IPB,NPB,J,DB,UB,VB,SB,HB,SPB,SPPB,PSIB,
     *                      PSIBN,3)
                 CALL BAYS(J,DB,UB,VB,SB,HB,SPB,SPPB,PSIB,PSIBN,3)
 550          CONTINUE
C ***** CALCULATE THE TOTAL WATER DEPTH FOR THIS TIME STEP *******
C ********** THE JAMES RIVER PART *********************************
              DO 1000 J=1,MAXJ
                 IF (IPJ(J) .NE.0) THEN
                    CALL STERM(IPJ,NPJ,J,DJAM,UJAM,VJAM,SJAM,HJAM,
     *                         SPJAM,SPPJAM,PSIJ,PSIJN,2)
                    CALL JAMESS(J,DJAM,UJAM,VJAM,SJAM,HJAM,SPJAM,SPPJAM,
     *                          PSIJ,PSIJN,2)
                 END IF
 1000         CONTINUE
 C ********* THE CHESAPEAKE BAY PART ******************************
              DO 2000 J=1,MAXB
                 CALL STERM(IPB,NPB,J,DB,UB,VB,SB,HB,SPB,SPPB,
     *                      PSIB,PSIBN,2)
                 CALL BAYS(J,DB,UB,VB,SB,HB,SPB,SPPB,PSIB,PSIBN,2)
 2000         CONTINUE
 C ***** CALCULATE THE VELOCITY COMPONENTS ************************
 C ********* THE JAMES RIVER PART *********************************
              DO 3000 J=1,MAXJ
                 IF (IPJ(J) .NE. 0) THEN
                    CALL DUTERM(IPJ,NPJ,J,DJAM,UJAM,VJAM,SJAM,DUJAM,
     *                          SHUPJAM,SHUJAM,DUPPJAM,DUPJAM,2,1)
                    CALL DVTERM(IPJ,NPJ,J,DJAM,UJAM,VJAM,SJAM,DVJAM,
     *                          SHVPJAM,SHVJAM,DVPPJAM,DVPJAM,2,1)
                    CALL JAMESV(J,DJAM,UJAM,VJAM,SJAM,DUJAM,DVJAM,
     *                 SHUPJAM,SHUJAM,DUPPJAM,DUPJAM,SHVPJAM,SHVJAM,
     *                 DVPPJAM,DVPJAM,2)
                 END IF
 3000         CONTINUE
 C ***** THE CHESAPEAKE BAY PART **********************************
              DO 4000 J=1,MAXB
                 CALL DUTERM(IPB,NPB,J,DB,UB,VB,SB,DUB,
     *                       SHUPB,SHUB,DUPPB,DUPB,2,2)
                 CALL DVTERM(IPB,NPB,J,DB,UB,VB,SB,DVB,
     *                       SHVPB,SHVB,DVPPB,DVPB,2,2)
                 CALL BAYV(J,DB,UB,VB,SB,DUB,DVB,SHUPB,SHUB,DUPPB,DUPB,
     *                  SHVPB,SHVB,DVPPB,DVPB,2)
 4000         CONTINUE
 C ***** REPLACED THE DEPTH-AVERAGED CONCENTRATION VALUES WITH ***
 C ***** NEW ONES                                             ***
 C ********* THE JAMES RIVER PART *********************************
              DO 5000 J=1,MAXJ
                 IF (IPJ(J) .NE. 0) THEN
                    CALL STERM (IPJ,NPJ,J,DJAM,UJAM,VJAM,SJAM,HJAM,
     *                          SPJAM,SPPJAM,PSIJ,PSIJN,4)
                    CALL JAMESS (J,DJAM,UJAM,VJAM,SJAM,HJAM,SPJAM,SPPJAM,
     *                           PSIJ,PSIJN,4)
                 END IF
 5000         CONTINUE
 C ********* THE CHESAPEAKE BAY PART ******************************
              DO 6000 J=1,MAXB
                 CALL STERM(IPB,NPB,J,DB,UB,VB,SB,HB,SPB,SPPB,
     *                      PSIB,PSIBN,4)
                 CALL BAYS (J,DB,UB,VB,SB,HB,SPB,SPPB,PSIB,PSIBN,4)
```

```
 6000      CONTINUE
C ***** THE INPUT FORCING FUNCTION DUE TO THE TIDAL CONTROL AT ***
C ***** THE MOUTH OF CHESAPEAKE BAY                            ***
           CYCLE=MOD(RTIME,(T1+T2))
           IF ((CYCLE .LE.T1) .AND. (CYCLE .GE. 0.0)) THEN
              SB(18,0)=1.51*COS(3.14159*CYCLE/T1)+1.31
           ELSE
              SB(18,0)=-1.54*COS(3.14159*(CYCLE-T1)/T2)+1.34
           END IF
           DB(18,0)=SB(18,0)+HB(18,0)
            DO 205 I=16,18
              IF (I .NE. 18) THEN
                 SB(I,0)=SB(18,0)
                 DB(I,0)=SB(I,0)+HB(I,0)
              END IF
              J=I-15
              SB(18,J)=SB(18,0)
              DB(18,J)=SB(18,J)+HB(18,J)
  205       CONTINUE
C ***** SET THE WATER SURFACE DEPTH OF THE EXTERIOR GRID POINTS **
C ***** TO BE THE ADJACENT INTERIOR ONES                         **
            SB(13,48)=SB(13,47)
            DB(13,48)=SB(13,48)+HB(13,48)
            SB(5,19)=SB(6,19)
            DB(5,19)=SB(5,19)+HB(5,19)
            SB(5,20)=SB(6,20)
            DB(5,20)=SB(5,20)+HB(5,20)
            SB(6,13)=SB(7,13)
            DB(6,13)=SB(6,13)+HB(6,13)
            SB(6,12)=SB(7,12)
            DB(6,12)=SB(6,12)+HB(6,12)
            SJAM(0,9)=SJAM(1,9)
            DJAM(0,9)=SJAM(0,9)+HJAM(0,9)
            SJAM(0,8)=SJAM(1,8)
            DJAM(0,8)=SJAM(0,8)+HJAM(0,8)
C ***** SET THE CONCENTRATION OF THE EXTERIOR GRIDS TO **
C ***** BE THE ADJACENT INTERIOR ONES *******************
            DO 10 I=1,3
   10          PSIJ(I,10)=PSIJ(I,9)
            PSIJ(8,9)=PSIJ(8,8)
            PSIJ(7,7)=PSIJ(8,7)
            PSIJ(10,6)=PSIJ(11,6)
            PSIJ(11,8)=PSIJ(11,7)
            PSIJ(14,8)=PSIJ(14,7)
            PSIJ(18,4)=PSIJ(18,5)
            PSIJ(19,5)=PSIJ(20,5)
            PSIJ(20,7)=PSIJ(20,6)
            PSIJ(21,6)=PSIJ(21,5)
            DO 20 J=3,4
   20          PSIJ(20,J)=PSIJ(21,J)
            PSIJ(22,5)=PSIJ(22,4)
            PSIJ(22,2)=PSIJ(23,2)
            DO 30 I=23,24
   30          PSIJ(I,4)=PSIJ(I,3)
            PSIJ(24,1)=PSIB(1,1)
            DO 40 I=1,2
   40          PSIB(I,3)=PSIB(I,2)
            PSIB(4,2)=PSIB(5,2)
            PSIB(5,0)=PSIB(5,1)
C ***** CALCULATE THE AVERAGED VOLUME TRANSPORT COMPONENT FOR ****
C ***** HYDRODYNAMIC PART AND THE DEPTH-AVERAGED CONCENTRATION ***
C ***** FOR THE TRANSPORT-DISPERSION PART DURING ONE TIDAL      ***
C ***** CYCLE                                                   ***
            IF (TIME .GT. NT1) THEN
               IF (TIME .LE. NT2) CALL AVE(NNT1)
               IF (TIME .EQ. NT2) GO TO 1
```

```
                IF (TIME .GT. NT2) CALL AVE(NNT2)
                IF (TIME .EQ. NTIME) GO TO 1
             END IF
             GO TO 777
    1        DO 207 J=1,48
                DO 207 I=1,26
                   IF (J .LE. 10)THEN
                      IF (DJAM(I,J) .NE. .0)
     *                   CONJ(I,J)=APJAM(I,J)/DJAM(I,J)
                   ENDIF
                   IF (DB(I,J) .NE. .0)
     *                CONB(I,J)=APB(I,J)/DB(I,J)
  207        CONTINUE
             DO 177 J=1,50
                IF (J .LE. 10) THEN
                   WRITE(6,7050) (AUJAM(I,J),I=1,26),
     *                           (AVJAM(I,J),I=1,26)
                   WRITE(7,7050) (CONJ(I,J),I=1,26)
                ENDIF
                WRITE(6,7050) (AUB(I,J),I=1,26),
     *                        (AVB(I,J),I=1,26)
                IF (J .LE. 48) WRITE(7,7050) (CONB(I,J),I=1,26)
  177        CONTINUE
 7050        FORMAT(1X,10E12.4/)
             CALL INIT1(10,AUJAM,AVJAM,APJAM)
             CALL INIT1(50,AUB,AVB,APB)
C ***** OUTPUT THE VELOCITY COMPONENT AND DEPTH AVERAGED **********
C ***** CONCENTRATION FOR EACH 2-HR INTERVAL                   *****
C            IF (TIME .GE. 8640) THEN
C            IF (MOD(TIME,120) .EQ. 0) THEN
CC           DO 97 J=1,10
CC 97           WRITE(6,7050) (UJAM(I,J),I=1,26),
CC    *                       (VJAM(I,J),I=1,26)
 7050        FORMAT(1X,'UJAM='/2X,13F8.3/1X,13F8.3/1X,
C     *            'VJAM='/2X,13F8.3/1X,13F8.3)
CC           DO 207 J=1,10
  207           WRITE(7,8050) (PSIJ(I,J),I=1,26)
CC           DO 107 J=1,48
  107           WRITE(6,7060) (UB(I,J),I=1,26),
CC    *                       (VB(I,J),I=1,26)
 7060        FORMAT(1X,'UB='/2X,13F8.3/1X,13F8.3/1X,'VB='/2X,
     *             13F8.3/1X,13F8.3)
CC           DO 197 J=1,48
CC197           WRITE(7,8050) (PSIB(I,J),I=1,26)
 9050           FORMAT(1X,'PSIB='/2X,13F8.3/1X,13F8.3)
 9060           FORMAT(1X,'PSIJ='/2X,13F8.3/1X,13F8.3)
C            END IF
C            END IF
 8050   FORMAT(10F10.4/)
  777     CONTINUE
          STOP
          END
C
C
          SUBROUTINE INIT(MAX,D,U,V,H,S,DU,DV)
C *****************************************************************
C     SUBROUTINE INIT IS TO INITIALIZE THE VARIABLES
C *****************************************************************
          DIMENSION D(0:26,0:50),U(0:26,0:50),V(26,0:50),
     *              H(0:26,0:50),S(0:26,0:50),DU(26,50),DV(26,50)
C
          DO 9 J=0,MAX
             DO 9 I=0,26
                U(I,J)=0.0
                IF (I .NE. 0) V(I,J)=0.0
                S(I,J)=0.0
```

```
          D(I,J)=H(I,J)+S(I,J)
          IF (( I .NE. 0) .AND. (J .NE. 0)) THEN
             DU(I,J)=0.0
             DV(I,J)=0.0
          END IF
    9   CONTINUE
        RETURN
        END
C
C
        SUBROUTINE DUTERM(IP,NP,J,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,
     *                 ID1,ID2)
C ****************************************************************
C       SUBROUTINE DUTERM CONTROLS THE CALCULATION NUMBER OF     *
C       HORIZONTAL VOLUME TRANSPORT COMPONENTS FOR EACH ROW      *
C ****************************************************************
        DIMENSION IP(50),NP(50),SHUP(26,50),SHU(26,50),
     *            DUPP(26,50),DUP(26,50),
     *            D(0:26,0:50),U(0:26,0:50),V(26,0:50)
        REAL K,LEAP,KK
        INTEGER TIME
        DIMENSION S(0:26,0:50),DU(26,50)
        COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
C
        NN=IP(J)+NP(J)-1
        DO 200 I=IP(J),NN
           IF (I .NE. NN) CALL UTERM(I,J,D,U,V,S,DU,SHUP,SHU,
     *                               DUPP,DUP,ID1)
           IF (ID2 .EQ. 2) THEN
              IF (J .LE. 3) CALL UTERM(NN,J,D,U,V,S,DU,SHUP,SHU,
     *                                DUPP,DUP,ID1)
           END IF
  200   CONTINUE
        RETURN
        END
C
C
        SUBROUTINE DVTERM(IP,NP,J,D,U,V,S,DV,SHVP,SHV,
     *                  DVPP,DVP,ID1,ID2)
C ****************************************************************
C       SUBROUTINE DVTERM CONTROLS THE CALCULATION NUMBER OF     *
C       VERTICAL VOLUME TRANSPORT COMPONENTS FOR EACH ROW        *
C ****************************************************************
        DIMENSION IP(50),NP(50),SHVP(26,50),SHV(26,50),
     *            DVPP(26,50),DVP(26,50),
     *            D(0:26,0:50),U(0:26,0:50),V(26,0:50)
        REAL K,LEAP,KK
        INTEGER TIME
        DIMENSION S(0:26,0:50),DV(26,50)
        COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
C
        IF (ID2 .EQ.1) IJ=2
        IF (ID2 .EQ.2) IJ=1
        IF (J .NE. IJ) THEN
           IPP=MAX(IP(J),IP(J-1))
           IN1=IP(J-1)+NP(J-1)-1
           IN2=IP(J)+NP(J)-1
           MM=MIN(IN1,IN2)
           DO 300 I=IPP,MM
              CALL VTERM(I,J,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
  300      CONTINUE
        END IF
        RETURN
        END
C
C
```

```
      SUBROUTINE JAMESV(J,D,U,V,S,DU,DV,SHUP,SHU,DUPP,DUP,
     *                     SHVP,SHV,DVPP,DVP,ID1)
C ********************************************************************
C       SUBROUTINE JAMESV CONCLUDES THE RANDOM PART OF VOLUME        *
C       TRANSPORT CALCULATION WHICH ARE NOT INCLUDED IN THE          *
C       DUTERM & DVTERM  FOR THE JAMES RIVER                         *
C ********************************************************************
      DIMENSION D(0:26,0:50),U(0:26,0:50),V(26,0:50),
     *          S(0:26,0:50),DU(26,50),DV(26,50),
     *          SHUP(26,50),SHU(26,50),DUPP(26,50),DUP(26,50),
     *          SHVP(26,50),SHV(26,50),DVPP(26,50),DVP(26,50)
      REAL K,LEAP,KK
      INTEGER TIME
      COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
C
      IF (J .EQ. 2) CALL UTERM(24,2,D,U,V,S,DU,SHUP,SHU,
     *                     DUPP,DUP,ID1)
      IF (J .EQ. 6) CALL VTERM(18,6,D,U,V,S,DV,SHVP,SHV,
     *                     DVPP,DVP,ID1)
      IF (J .EQ. 7) CALL VTERM(14,7,D,U,V,S,DV,SHVP,SHV,
     *                     DVPP,DVP,ID1)
      RETURN
      END
C
C
      SUBROUTINE BAYV(J,D,U,V,S,DU,DV,SHUP,SHU,DUPP,DUP,
     *                     SHVP,SHV,DVPP,DVP,ID1)
C ********************************************************************
C       SUBROUTINE BAYV CONCLUDES THE RANDOM PART OF THE VOLUME      *
C       TRANSPORT CALCULATION WHICH ARE NOT INCLUDED IN THE          *
C       DUTERM & DVTERM FOR THE CHESAPEAKE BAY                       *
C ********************************************************************
      DIMENSION D(0:26,0:50),U(0:26,0:50),V(26,0:50),
     *          S(0:26,0:50),DU(26,50),DV(26,50),
     *          SHUP(26,50),SHU(26,50),DUPP(26,50),DUP(26,50),
     *          SHVP(26,50),SHV(26,50),DVPP(26,50),DVP(26,50)
      REAL K,LEAP,KK
      INTEGER TIME
      COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
C
      IF (J .EQ. 1) THEN
         DO 5 I=1,4
    5       CALL UTERM(I,1,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
         DO 55 I=16,17
   55       CALL VTERM(I,1,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      END IF
      IF (J .EQ. 2) THEN
         CALL UTERM(1,2,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
         CALL VTERM(5,2,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
         DO 60 I=1,2
   60       CALL VTERM(I,2,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      END IF
      IF (J .EQ. 8) THEN
         DO 10 I=4,5
   10       CALL UTERM(I,8,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
         DO 65 I=5,6
   65       CALL VTERM(I,8,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      END IF
      IF (J .EQ. 9) THEN
         CALL UTERM(4,9,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
         DO 70 I=4,5
   70       CALL VTERM(I,9,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      END IF
      IF (J .EQ. 19) THEN
         DO 15 I=21,24
            CALL UTERM(I,19,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
```

```
15           CALL VTERM(I,19,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      END IF
      IF (J .EQ. 26) THEN
         CALL UTERM(18,26,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
         CALL VTERM(15,26,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
         CALL VTERM(18,26,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      END IF
      IF (J .EQ. 25) THEN
         CALL VTERM(15,25,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
         CALL VTERM(18,25,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      END IF
      IF (J .EQ. 36) THEN
         DO 20 I=7,8
20          CALL UTERM (I,36,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
         DO 80 I=7,9
80          CALL VTERM(I,36,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      END IF
      IF(J .EQ. 32)CALL VTERM(10,32,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      IF (J .EQ. 38) THEN
         DO 25 I=8,9
25          CALL UTERM(I,38,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
      END IF
      IF (J .EQ. 39) THEN
         CALL UTERM(10,39,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
         CALL VTERM(8,39,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
         CALL VTERM(10,39,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      END IF
      IF(J .EQ. 44)CALL VTERM(7,44,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      IF(J .EQ. 45)CALL VTERM(9,45,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
      RETURN
      END
C
C
      SUBROUTINE STERM(IP,NP,J,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
C *******************************************************************
C     SUBROUTINE STERM CONTROLS THE CALCULATION NUMBER OF           *
C     CHANGE IN WATER SURFACE FOR EACH ROW                          *
C *******************************************************************
      DIMENSION IP(50),NP(50),SP(26,50),SPP(26,50),
     *          D(0:26,0:50),U(0:26,0:50),V(26,0:50),
     *          S(0:26,0:50),H(0:26,0:50),PSI(-1:27,-1:50),
     *          PSIN(25,48)
      REAL K,LEAP,KK
      INTEGER TIME
      COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
      COMMON/MASS/ ARFAX, ARFAY
C
      NN=IP(J)+NP(J)-1
      DO 500 I=IP(J),NN
         CALL DEEP(I,J,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
500   CONTINUE
      RETURN
      END
C
C
      SUBROUTINE JAMESS(J,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
C *******************************************************************
C     SUBROUTINE JAMESS CONCLUDES THE RANDOM PART OF WATER          *
C     DEPTH CHANGE CALCULATION WHICH IS NOT INCLUDED IN THE         *
C     STERM FOR THE JAMES RIVER                                     *
C *******************************************************************
      DIMENSION D(0:26,0:50),U(0:26,0:50),V(26,0:50),
     *          S(0:26,0:50),H(0:26,0:50),SP(26,50),SPP(26,50),
     *          PSI(-1:27,-1:50),PSIN(25,48)
      REAL K,LEAP,KK
      INTEGER TIME
```

```
      COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
      COMMON/MASS/ ARFAX,ARFAY
C
      IF (J .EQ. 5) CALL DEEP(18,5,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      IF (J .EQ. 7) CALL DEEP(14,7,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      RETURN
      END
C
C
      SUBROUTINE BAYS(J,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
C *****************************************************************
C       SUBROUTINE BAYS CONCLUDES THE RANDOM PART OF WATER        *
C       DEPTH CHANGE CALCULATION WHICH IS NOT INCLUDED IN THE     *
C       STERM  FOR THE CHESAPEAKE BAY                             *
C *****************************************************************
      DIMENSION D(0:26,0:50),U(0:26,0:50),V(26,0:50),
     *          S(0:26,0:50),H(0:26,0:50),SP(26,50),SPP(26,50),
     *          PSI(-1:27,-1:50),PSIN(25,48)
      REAL K,LEAP,KK
      INTEGER TIME
      COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
      COMMON/MASS/ ARFAX,ARFAY
C
      IF (J .EQ. 1) THEN
         DO 105 I=1,5
 105        CALL DEEP(I,1,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 2) THEN
         DO 110 I=1,2
 110        CALL DEEP(I,2,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 8) THEN
         DO 115 I=4,6
 115        CALL DEEP(I,8,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 9) THEN
         DO 120 I=4,5
 120        CALL DEEP(I,9,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 19) THEN
         DO 125 I=21,25
 125        CALL DEEP(I,19,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 25) THEN
         CALL DEEP(15,25,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
         CALL DEEP(18,25,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 26) THEN
         CALL DEEP (15,26,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
         CALL DEEP(18,26,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
         CALL DEEP(19,26,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 31) CALL DEEP(10,31,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      IF (J .EQ. 36) THEN
         DO 130 I=7,9
 130        CALL DEEP(I,36,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 38) THEN
         DO 135 I=8,10
 135        CALL DEEP(I,38,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 39) THEN
         DO 140 I=10,11
 140        CALL DEEP(I,39,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      END IF
      IF (J .EQ. 44) CALL DEEP(7,44,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
```

```
      IF (J .EQ. 45) CALL DEEP(9,45,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
      RETURN
      END
C
C
      SUBROUTINE UTERM(I,J,D,U,V,S,DU,SHUP,SHU,DUPP,DUP,ID1)
C ****************************************************************
C     SUBROUTINE UTERM CALCULATES THE HORIZONTAL VOLUME           *
C     TRANSPORT COMPONENT WITH FINITE DIFFERENCE SCHEME FOR       *
C     ID1 = 1, AND CALCULATES THE HORIZONTAL VELOCITY             *
C     COMPONENT FOR ID1 = 2                                       *
C ****************************************************************
      DIMENSION SHUP(26,50),SHU(26,50),DUPP(26,50),
     *          DUP(26,50),
     *          D(0:26,0:50),U(0:26,0:50),V(26,0:50),
     *          S(0:26,0:50),DU(26,50)
      REAL K,LEAP,KK
      INTEGER TIME
      COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
C
      IF (ID1 .EQ. 1) THEN
         II=I+1
         JJ=J+1
         III=II+1
         IF (TIME .NE. 1) THEN
            SHUP(II,J)=SHU(II,J)
            DUP(II,J)=DU(II,J)
         END IF
         SHU(II,J)=2.*DT*K*(U(II,J)*(U(II,J)**2+
     *        ((VXUY(U,V,II,J,1)+VXUY(U,V,II,JJ,1))/2.)**2)**0.5)
         IF (TIME .EQ. 1) THEN
            SHUP(II,J)=SHU(II,J)
            DUPP(II,J)=DU(II,J)
            DUP(II,J)=DUPP(II,J)
         END IF
         EUA=DT*((DUV(D,U,V,III,J,1)+DUV(D,U,V,II,J,1))*
     *       UXVY(U,V,III,J,1)-(DUV(D,U,V,II,J,1)+
     *       DUV(D,U,V,I,J,1))*UXVY(U,V,II,J,1))/DX
         EUB=DT*((DUV(D,U,V,II,JJ,2)+DUV(D,U,V,I,JJ,2))*
     *       VXUY(U,V,II,JJ,2)-(DUV(D,U,V,II,J,2)+
     *       DUV(D,U,V,I,J,2))*VXUY(U,V,II,J,2))/DY
         EUC=DT*F*(DUV(D,U,V,II,JJ,2)+DUV(D,U,V,I,JJ,2)+
     *       DUV(D,U,V,II,J,2)+DUV(D,U,V,I,J,2))/2
         EUD=DT*G*(D(I,J)+D(II,J))*(S(II,J)-S(I,J))/DX
         IF (II .EQ. 18)THEN
            IF (J .LE. 3)
     *         EUA= DT*(-(DUV(D,U,V,II,J,1)+DUV(D,U,V,I,J,1))*
     *              UXVY(U,V,II,J,1))/DX
         END IF
         DU(II,J)=DUPP(II,J)-(EUA+EUB-EUC+EUD-2.*DT*W+
     *           SHUP(II,J))/LEAP
         DUPP(II,J)=DUP(II,J)
      ELSE
         II=I+1
         U(II,J)=DU(II,J)*2./(D(II,J)+D(I,J))
      END IF
      RETURN
      END
C
C
      SUBROUTINE VTERM(I,J,D,U,V,S,DV,SHVP,SHV,DVPP,DVP,ID1)
C ****************************************************************
C     SUBROUTINE VTERM CALCULATES THE VERTICAL VOLUME             *
C     TRANSPORT COMPONENT WITH FINITE DIFFERENCE SCHEME  FOR      *
C     ID1 = 1, AND CALCULATES THE VERTICAL VELOCITY COMPONENT     *
C     FOR ID1 = 2                                                 *
```

```
C *********************************************************************
      DIMENSION SHVP(26,50),SHV(26,50),DVPP(26,50),DVP(26,50),
     *          D(0:26,0:50),U(0:26,0:50),V(26,0:50),
     *          S(0:26,0:50),DV(26,50)
      REAL K,LEAP,KK
      INTEGER TIME
      COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
C
      IF (ID1 .EQ. 1) THEN
         II=I+1
         JJ=J+1
         J1=J-1
         IF (TIME .NE. 1) THEN
            SHVP(I,J)=SHV(I,J)
            DVP(I,J)=DV(I,J)
         END IF
         SHV(I,J)=2.*DT*K*(V(I,J)*(V(I,J)**2+
     *      ((VXUY(U,V,I,J,2)+VXUY(U,V,II,J,2))/2.)**2)**0.5)
         IF (TIME .EQ. 1) THEN
            SHVP(I,J)=SHV(I,J)
            DVPP(I,J)=DV(I,J)
            DVP(I,J)=DVPP(I,J)
         END IF
         EVA=DT*((DUV(D,U,V,II,J,1)+DUV(D,U,V,II,J1,1))*
     *       VXUY(U,V,II,J,1)-(DUV(D,U,V,I,J,1)+
     *       DUV(D,U,V,I,J1,1))*VXUY(U,V,I,J,1))/DX
         EVB=DT*((DUV(D,U,V,I,JJ,2)+DUV(D,U,V,I,J,2))*
     *       UXVY(U,V,I,JJ,2)-(DUV(D,U,V,I,J,2)+
     *       DUV(D,U,V,I,J1,2))*UXVY(U,V,I,J,2))/DY
         EVC=DT*F*(DUV(D,U,V,II,J,1)+DUV(D,U,V,I,J,1)+
     *       DUV(D,U,V,II,J1,1)+DUV(D,U,V,I,J1,1))/2.
         EVD=DT*G*(D(I,J1)+D(I,J))*(S(I,J)-S(I,J1))/DY
         IF (J .EQ. 1) THEN
            IF ((I .EQ. 16).OR.(I .EQ. 17))
     *         EVB= DT*((DUV(D,U,V,I,JJ,2)+DUV(D,U,V,I,J,2))*
     *              UXVY(U,V,I,JJ,2))/DY
         END IF
         DV(I,J)=DVPP(I,J)-(EVA+EVB+EVC+EVD-2.*DT*W+
     *        SHVP(I,J))/LEAP
         DVPP(I,J)=DVP(I,J)
      ELSE
         J1=J-1
         V(I,J)=DV(I,J)*2.0/(D(I,J)+D(I,J1))
      END IF
      RETURN
      END
C
C
      SUBROUTINE DEEP(I,J,D,U,V,S,H,SP,SPP,PSI,PSIN,ID1)
C *********************************************************************
C     SUBROUTINE DEEP CALCULATES THE CHANGE OF WATER DEPTH FOR *
C     ID1 = 1, THE TOTAL WATER DEPTH FOR ID1 = 2, THE DEPTH-   *
C     AVERAGED CONCENTRATION FOR ID1 = 3, AND REPLACES THE NEW *
C     DEPTH-AVERAGED CONCENTRATION FOR THE OLD ONE FOR ID1 = 4 *
C *********************************************************************
      DIMENSION SP(26,50),SPP(26,50),
     *          D(0:26,0:50),U(0:26,0:50),V(26,0:50),
     *          S(0:26,0:50),H(0:26,0:50),PSI(-1:27,-1:50),
     *          PSIN(25,48)
      REAL K,LEAP,KK
      INTEGER TIME
      COMMON/PARA/ K,F,W,G,DT,DX,DY,LEAP,TIME,KK
      COMMON/MASS/ ARFAX, ARFAY
C
      IN1=1
      IN2=1
```

```
         IN3=1
         IN4=1
         IF (ID1 .EQ. 1) THEN
            II=I+1
            JJ=J+1
            IF (TIME .NE. 1) SP(I,J)=S(I,J)
            IF (TIME .EQ. 1) THEN
               SPP(I,J)=S(I,J)
               SP(I,J)=SPP(I,J)
            END IF
            S(I,J)=SPP(I,J)-(2.*DT*(DUV(D,U,V,II,J,1)-
     *             DUV(D,U,V,I,J,1))/DX+2.*DT*
     *             (DUV(D,U,V,I,JJ,2)-DUV(D,U,V,I,J,2))/DY)/LEAP
            SPP(I,J)=SP(I,J)
         END IF
         IF (ID1 .EQ. 2) D(I,J)=H(I,J)+S(I,J)
         IF( ID1 .EQ. 3) THEN
           II=I+1
           JJ=J+1
           I1=I-1
           J1=J-1
           CR= U(II,J)* DT/ DX
           IF (CR .LT. 0.) IN1=2
           CT= V(I,JJ)* DT/ DY
           IF (CT .LT. 0.) IN2=2
           CL= U(I,J)* DT/ DX
           IF (CL .LT. 0.) IN3=2
           CB= V(I,J)* DT/ DY
           IF (CB .LT. 0.) IN4=2
             FR= CR*(0.5*(PSI(I,J)+PSI(II,J))-0.5*CR*DELTAX(PSI,I,J)+
     *            (0.5*ARFAX-(1.0-CR**2)/6.0)*DDELTAX(PSI,I,J,IN1))-
     *            ARFAX*DELTAX(PSI,I,J)+0.5*ARFAX*CR*DDELTAX(PSI,I,J,IN1)
             FT= CT*(0.5*(PSI(I,J)+PSI(I,JJ))-0.5*CT*DELTAY(PSI,I,J)+
     *            (0.5*ARFAY-(1.0-CT**2)/6.0)*DDELTAY(PSI,I,J,IN2))-
     *            ARFAY*DELTAY(PSI,I,J)+0.5*ARFAY*CT*DDELTAY(PSI,I,J,IN2)
             FL= CL*(0.5*(PSI(I,J)+PSI(I1,J))-0.5*CL*DELTAX(PSI,I1,J)+
     *            (0.5*ARFAX-(1.0-CL**2)/6.0)*DDELTAX(PSI,I1,J,IN3))-
     *       ARFAX*DELTAX(PSI,I1,J)+0.5*ARFAX*CL*DDELTAX(PSI,I1,J,IN3)
             FB= CB*(0.5*(PSI(I,J)+PSI(I,J1))-0.5*CB*DELTAY(PSI,I,J1)+
     *            (0.5*ARFAY-(1.0-CB**2)/6.0)*DDELTAY(PSI,I,J1,IN4))-
     *       ARFAY*DELTAY(PSI,I,J1)+0.5*ARFAY*CB*DDELTAY(PSI,I,J1,IN4)
             PSIN(I,J)= PSI(I,J)*(1.-KK*DT/86400.)-FR+FL-FT+FB
         END IF
         IF (ID1 .EQ. 4) THEN
            PSI(I,J)=PSIN(I,J)
         ENDIF
         RETURN
         END
C
C
C
         FUNCTION DUV(D,U,V,N,M,NM)
C *****************************************************************
C        FUNCTION DUV AVERAGES THE HORIZONTAL VOLUME TRANSPORT     *
C        BETWEEN TWO ADJACENT GRID DEPTH                           *
C *****************************************************************
         DIMENSION D(0:26,0:50),U(0:26,0:50),V(26,0:50)
C
         IF (NM .EQ. 1) THEN
            NN=N-1
            DUV=(D(NN,M)+D(N,M))*U(N,M)/2.
         ELSE
            MM=M-1
            IF (MM .EQ. -1) MM=0
            DUV=(D(N,MM)+D(N,M))*V(N,M)/2.
         END IF
```

```
      RETURN
      END
C
C
      FUNCTION UXVY(U,V,N,M,NM)
C ******************************************************************
C     FUNCTION UXVY AVERAGES THE HORIZONTAL VELOCITIES IN X-DI *
C     AND VERTICAL VELOCITIES IN Y-DI                          *
C ******************************************************************
      DIMENSION U(0:26,0:50),V(26,0:50)
C
      IF (NM .EQ. 1) THEN
         NN=N-1
         UXVY=(U(N,M)+U(NN,M))/2.
      ELSE
         MM=M-1
         UXVY=(V(N,M)+V(N,MM))/2.
      END IF
      RETURN
      END
C
C
      FUNCTION VXUY(U,V,N,M,NM)
C ******************************************************************
C     FUNCTION VXUY AVERAGES THE VERTICAL VELOCITIES IN X-DI   *
C     AND HORIZONTAL VELOCITIES IN Y-DI                        *
C ******************************************************************
      DIMENSION U(0:26,0:50),V(26,0:50)
C
      IF (NM .EQ. 1) THEN
         NN=N-1
         VXUY=(V(N,M)+V(NN,M))/2.
      ELSE
         MM=M-1
         VXUY=(U(N,M)+U(N,MM))/2.
      END IF
      RETURN
      END
C
C
   FUNCTION DELTAX(PSI,N,M)
C ******************************************************************
C     FUNCTION DELTAX CALCULATES THE FORWARD DIFFERENCE OF     *
C     PSI(N,M) IN THE X-DI                                     *
C ******************************************************************
   DIMENSION PSI(-1:27,-1:50)
C
   NX= N+1
   DELTAX= PSI(NX,M)-PSI(N,M)
   RETURN
   END
C
C
   FUNCTION DDELTAX(PSI,N,M,ID)
C ******************************************************************
C     FUNCTION DDELTAX CALCULATES THE CENTRAL DIFFERENCE  OF   *
C     PSI(NN,M) IN THE X-DI                                    *
C ******************************************************************
   DIMENSION PSI(-1:27,-1:50)
C
   NN=N
   IF (ID .EQ. 2) NN=N+1
   NX=NN+1
   NNX=NN-1
   DDELTAX= PSI(NX,M)-2.0*PSI(NN,M)+PSI(NNX,M)
```

```
      RETURN
      END
C
C
      FUNCTION DELTAY(PSI,N,M)
C ********************************************************************
C        FUNCTION DELTAY CALCULATES THE FORWARD DIFFERENCE OF        *
C        PSI(N,M) IN THE Y-DI                                        *
C ********************************************************************
      DIMENSION PSI(-1:27,-1:50)
C
      MY= M+1
      DELTAY= PSI(N,MY)-PSI(N,M)
      RETURN
      END
C
C
      FUNCTION DDELTAY(PSI,N,M,ID)
C ********************************************************************
C        FUNCTION DDELTAY CALCULATES THE CENTRAL DIFFERENCE OF       *
C        PSI(N,MM) IN THE Y-DI                                       *
C ********************************************************************
      DIMENSION PSI(-1:27,-1:50)
C
      MM=M
      IF (ID .EQ. 2)MM= M+1
      MY=MM+1
      MMY=MM-1
      DDELTAY= PSI(N,MY)-2.0*PSI(N,MM)+PSI(N,MMY)
      RETURN
      END
C
C
        SUBROUTINE INIT1(MAX,AU,AV,AP)
C ********************************************************************
C       SUBROUTINE INIT1 INITIALIZES THE AVERAGED VARIABLES          *
C ********************************************************************
        DIMENSION AU(26,50),AV(26,50),AP(26,50)
C
        DO 9 J=1,MAX
           DO 9 I=1,26
              AU(I,J)=0.0
              AV(I,J)=0.0
              AP(I,J)=0.0
    9   CONTINUE
        RETURN
        END
C
C
        SUBROUTINE AVE(NNT)
C ********************************************************************
C       SUBROUTINE AVE AVERAGES THE VOLUME TRANSPORT COMPONENTS      *
C       AND THE DEPTH-AVERAGED CONCENTRATIONS DURING ONE  TIDAL      *
C       CYCLE                                                        *
C ********************************************************************
        DIMENSION AUJAM(26,10),AVJAM(26,10),AUB(26,50),
     *            AVB(26,50),APJAM(26,10),APB(26,48),
     *            DUJAM(26,10),DVJAM(26,10),DUB(26,50),DVB(26,50),
     *            PSIJ(-1:27,-1:11),PSIB(-1:27,-1:50)
        INTEGER TIME
        COMMON/AVERAGE/ AUJAM,AVJAM,AUB,AVB,APJAM,APB
        COMMON/AVE1/ DUJAM,DVJAM,DUB,DVB,PSIJ,PSIB
C
CC      WRITE(2,8051) TIME,NNT
 8051   FORMAT(1X,'TIME=',I5,'NNT=',I5)
        DO 117 J=1,48
```

```
      DO 117 I=1,26
         IF (J .LE. 10) THEN
            AUJAM(I,J)=AUJAM(I,J)+DUJAM(I,J)/NNT
            AVJAM(I,J)=AVJAM(I,J)+DVJAM(I,J)/NNT
            APJAM(I,J)=APJAM(I,J)+PSIJ(I,J)/NNT
         ENDIF
         AUB(I,J)=AUB(I,J)+DUB(I,J)/NNT
         AVB(I,J)=AVB(I,J)+DVB(I,J)/NNT
         APB(I,J)=APB(I,J)+PSIB(I,J)/NNT
117   CONTINUE
      RETURN
      END
```

REFERENCES

1. Blumberg, A. F. 1977. Numerical Tidal Model of Chesapeake Bay. *Journal of the Hydraulic Division*, ASCE, Vol. 103, No. HY1, pp.1-9.

2. Bedford, K. W. 1985. *Selection of Turbulence and Mixing Parameterization for Estuary Water Quality Models.* Final Report, Environmental Impact Research Program, US Army Corps of Engineers, 153p.

3. Hall, R. W. and Chapman, R. S. 1985. *Two-Dimensional QUICKEST Solution of the Depth-Averaged Transport- Dispersion Equation.* Final Report, Environmental Impact Research Program, US Army Corps of Engineers, 29p.

4. HydroQual, 1987. *Development of a Coupled Hydrodynamic/Water Quality Model of the Eutrophication and Anoxia Processes of the Chesapeake Bay.* pp.1-12.

5. Lung, W. S. 1986a. Assessing Phosphorus Control in the James River Basin. *Journal of Environmental Engineering*, ASCE, Vol. 112, No. 1, pp.44-60.

6. Lung, W. S. 1986b. Phosphorus Loads to the Chesapeake Bay : A perspective. *Journal of Water Pollution Control Federation,* Vol. 58, No. 7, pp.749-756.

7. Lung, W. S. 1987. *Eutrophication Modeling of James Estuary, Virginia.* Final Report, Univ. of Virginia, Department of Civil Engineering , 40p.

8. Leendertse, J. J. 1967. *Aspects of a Computational Model for Long-Period Water-Wave Propagation.* United State Air Force Project Rand, RM-5294-PR, 165p.

9. Leonard, B. P. 1978. A Stable and Accurate Convective Modeling Procedure Based on Quadratic Upstream Interpolation. *Computer Method in Applied Mechanics and Engineering,* North-Holland Publishing Co., pp.59-98.

10. Lilly, D. K. 1965. On the Computational Stability of Numerical Solutions of Time-Dependent Non-Linear Geophysical Fluid Problems. *Monthly Weather review,* Vol. 93, No. 1, pp.83-98.

11. Thomann, R. V. and Mueller, J. A. 1987. *Principles of Surface Water Quality Modeling and Control.* Harper & Row, Publishers, New York, pp.91-172.

UNIVERSITY OF VIRGINIA
School of Engineering and Applied Science

The University of Virginia's School of Engineering and Applied Science has an undergraduate enrollment of approximately 1,500 students with a graduate enrollment of approximately 560. There are 150 faculty members, a majority of whom conduct research in addition to teaching.

Research is a vital part of the educational program and interests parallel academic specialties. These range from the classical engineering disciplines of Chemical, Civil, Electrical, and Mechanical and Aerospace to newer, more specialized fields of Biomedical Engineering, Systems Engineering, Materials Science, Nuclear Engineering and Engineering Physics, Applied Mathematics and Computer Science. Within these disciplines there are well equipped laboratories for conducting highly specialized research. All departments offer the doctorate; Biomedical and Materials Science grant only graduate degrees. In addition, courses in the humanities are offered within the School.

The University of Virginia (which includes approximately 2,000 faculty and a total of full-time student enrollment of about 16,400), also offers professional degrees under the schools of Architecture, Law, Medicine, Nursing, Commerce, Business Administration, and Education. In addition, the College of Arts and Sciences houses departments of Mathematics, Physics, Chemistry and others relevant to the engineering research program. The School of Engineering and Applied Science is an integral part of this University community which provides opportunities for interdisciplinary work in pursuit of the basic goals of education, research, and public service.