# A Flow-Simulation Model of the Tidal Potomac River

A Water-Quality Study of the Tidal Potomac River and Estuary

United States Geological Survey Water-Supply Paper 2234–D

Chapter D

# A Flow-Simulation Model of the Tidal Potomac River

By RAYMOND W. SCHAFFRANEK

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A WATER-QUALITY STUDY OF THE TIDAL POTOMAC RIVER AND ESTUARY

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# FOREWORD

Tidal rivers and estuaries are very important features of the Coastal Zone because of their immense biological productivity and their proximity to centers of commerce and population. Most of the shellfish and much of the local finfish consumed by man are harvested from estuaries and tidal rivers. Many of the world's largest shipping ports are located within estuaries. Many estuaries originate as river valleys drowned by rising sea level and are geologically ephemeral features, destined eventually to fill with sediments. Nutrients, heavy metals, and organic chemicals are often associated with the sediments trapped in estuaries. Part of the trapped nutrients may be recycled to the water column, exacerbating nutrient-enrichment problems caused by local sewage treatment plants, and promoting undesirable algae growth. The metals and organics may be concentrated in the food chain, further upsetting the ecology and threatening the shell and finfish harvests. Our knowledge of the processes governing these phenomena is limited, and the measurements needed to improve our understanding are scarce.

In response to an increasing awareness of the importance and delicate ecological balance of tidal rivers and estuaries, the U.S. Geological Survey began a 5-year interdisciplinary study of the tidal Potomac River and Estuary in October of 1977. The study encompassed elements of both the Water Resources Division's ongoing Research and River Quality Assessment Programs. The Division has been conducting research on various elements of the hydrologic cycle since 1894 and began intense investigation of estuarine processes in San Francisco Bay in 1968. The River Quality Assessment program began in 1973 at the suggestion of the Advisory Committee on Water Data for Public Use, which saw a special need to develop suitable information for river-basin planning and water-quality management. The Potomac assessment was the first to focus on a tidal river and estuary. In addition to conducting research into the processes governing water-quality conditions in tidal rivers and estuaries, the ultimate goals of the Potomac Estuary Study were to aid water-quality management decision-making for the Potomac, and to provide other groups with a rational and well-documented general approach for the study of tidal rivers and estuaries.

This interdisciplinary effort emphasized studies of the transport of the major nutrient species and of suspended sediment. The movement of these substances through five major reaches or control volumes of the tidal Potomac River and Estuary was determined during 1980 and 1981. This effort provided a framework on which to assemble a variety of investigations:

(1) The generation and deposition of sediments, nutrients, and trace metals from the Holocene to the present was determined by sampling surficial bottom sediments and analyzing their characteristics and distributions.

(2) Bottom-sediment geochemistry was studied and the effects of benthic exchange processes on water-column nutrient concentrations ascertained.

(3) Current-velocity and water-surface-elevation data were collected to calibrate and verify a series of one- and two-dimensional hydrodynamic flow and transport models.

(4) Measurements from typical urban and rural watersheds were extrapolated to provide estimates of the nonpoint sources of sediments, nutrients, and biochemical oxygen demand during 1980 and 1981.

(5) Intensive summertime studies were conducted to determine the effects of local sewage-treatment-plant effluents on dissolved-oxygen levels in the tidal Potomac River.

(6) Species, numbers, and net productivity of phytoplankton were determined to evaluate their effect on nutrients and dissolved oxygen.

(7) Wetland studies were conducted to determine the present-day distribution and abundance of submersed aquatic vegetation, and to ascertain the important water-quality and sediment parameters influencing this distribution.

(8) Repetitive samples were collected to document the distribution and abundance of the macrobenthic infaunal species of the tidal river and estuary and to determine the effects of changes in environmental conditions on this distribution and abundance.

The reports in this Water-Supply Paper series document the technical aspects of the above investigations. The series also contains an overall introduction to the study, an integrated technical summary of the results, and an executive summary, which links the results with aspects of concern to water-quality managers.

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# SYMBOLS AND DEFINITIONS

| | | Units |
|---|---|---|
| $A$ | Area of cross section | $L^2$ |
| $B$ | Top width of cross section | L |
| $C_d$ | Water-surface drag coefficient | — |
| $g$ | Gravitational acceleration | $LT^{-2}$ |
| $k$ | Flow-resistance coefficient function | $T^2L^{-2/3}$ |
| $q$ | Lateral inflow per unit length of channel | $L^2T^{-1}$ |
| $Q$ | Flow discharge | $L^3T^{-1}$ |
| $R$ | Hydraulic radius of cross section | L |
| $t$ | Time | T |
| $\Delta t$ | Time increment | T |
| $u$ | Point flow velocity | $LT^{-1}$ |
| $U$ | Mean flow velocity | $LT^{-1}$ |
| $U_a$ | Wind velocity | $LT^{-1}$ |
| $x$ | Longitudinal channel distance | L |
| $\Delta x$ | Length increment | L |
| $Z$ | Water-surface elevation | L |
| $\alpha$ | Angle between wind direction and x-axis | Degrees |
| $\beta$ | Momentum coefficient | — |
| $\eta$ | Flow-resistance coefficient similar to Manning's *n* | $TL^{-1/3}$ |
| $\theta$ | Spatial-derivative weighting factor | — |
| $\xi$ | Wind-resistance coefficient | — |
| $\rho$ | Water density | $ML^{-3}$ |
| $\rho$ | Atmospheric density | $ML^{-3}$ |

# A Flow-Simulation Model of the Tidal Potomac River

*By* Raymond W. Schaffranek

**Abstract**

A one-dimensional model capable of simulating flow in a network of interconnected channels has been applied to the tidal Potomac River including its major tributaries and embayments between Washington, D.C., and Indian Head, Md. The model can be used to compute water-surface elevations and flow discharges at any of 66 predetermined locations or at any alternative river cross sections definable within the network of channels. In addition, the model can be used to provide tidal-interchange flow volumes and to evaluate tidal excursions and the flushing properties of the riverine system. Comparisons of model-computed results with measured water-surface elevations and discharges demonstrate the validity and accuracy of the model. Tidal-cycle flow volumes computed by the calibrated model have been verified to be within an accuracy of ±10 percent. Quantitative characteristics of the hydrodynamics of the tidal river are identified and discussed. The comprehensive flow data provided by the model can be used to better understand the geochemical, biological, and other processes affecting the river's water quality.

## INTRODUCTION

Previously identified, as well as unforeseen, water-quality problems continue to unfurl in the Potomac River. The river continues to be stressed to its maximum capacity as a repository for municipal sewage effluent and storm runoff from the Washington, D.C., metropolitan area. These conditions are likely to persist and to intensify in the future due to the expanding metropolitan population. Consequently, new avenues of water pollution control measures and technology need to be explored, and new and improved techniques for analyzing the river's condition need to be developed and employed. Such techniques will need to provide, for instance, comprehensive information on the flow dynamics of the river. Knowledge of the flow dynamics is fundamental to evaluating the river's flushing capacity for purposes of predicting the impact of future increased stresses.

The purpose of this report is to describe the design, verification, and application of a one-dimensional branched-network type flow model to the 50-km tidal riverine portion of the Potomac River from the head-of-tide near Chain Bridge in the vicinity of Washington, D.C., to Indian Head, Md. The primary objective of the development and implementation of the model is to evaluate the flow dynamics of the river and to provide the capability to quantify the time-varying flow field in the tidal river to assess its flushing capacity and retention properties. A second objective of the report is to provide a tool by which alternative water-management plans may be evaluated. The report briefly describes the branch-network flow model, its implementation to the tidal Potomac River system, its calibration and verification, and its utility in providing information in simplified and special-purpose formats for subsequent analyses of the flow dynamics and transport properties of the riverine system.

## THE TIDAL POTOMAC RIVER

The portion of the Potomac River from Indian Head, Md., to the head-of-tide near Chain Bridge in the northwest quadrant of the District of Columbia, a distance of nearly 50 km, is herein referred to as the tidal Potomac River (fig. 1). It is this riverine portion of the Potomac Estuary that is of primary concern in this report. Also included in this system are the Anacostia River, Roosevelt Island Channel, Washington Channel, the Tidal Basin, and the Broad Creek, Piscataway Creek, Dogue Creek, Gunston Cove, Pohick Bay, and Accotink Bay tidal inlets.

The river downstream of Chain Bridge is confined for a short distance (approximately 5 km) to a narrow and deep but gradually expanding channel bounded by steep rocky banks and high bluffs. Downstream from Key Bridge, the river consists of a broad, shallow and rapidly expanding channel confined between banks of low-to-moderate relief. Several small shallow inlets, formed where small streams discharge into the river, create irregularities and indentations in the channel in the vicinity of and downstream from Wilson Bridge.

The cross-sectional area of the river expands over fortyfold between Chain Bridge and Indian Head and increases from approximately 232 $m^2$ at Chain Bridge to

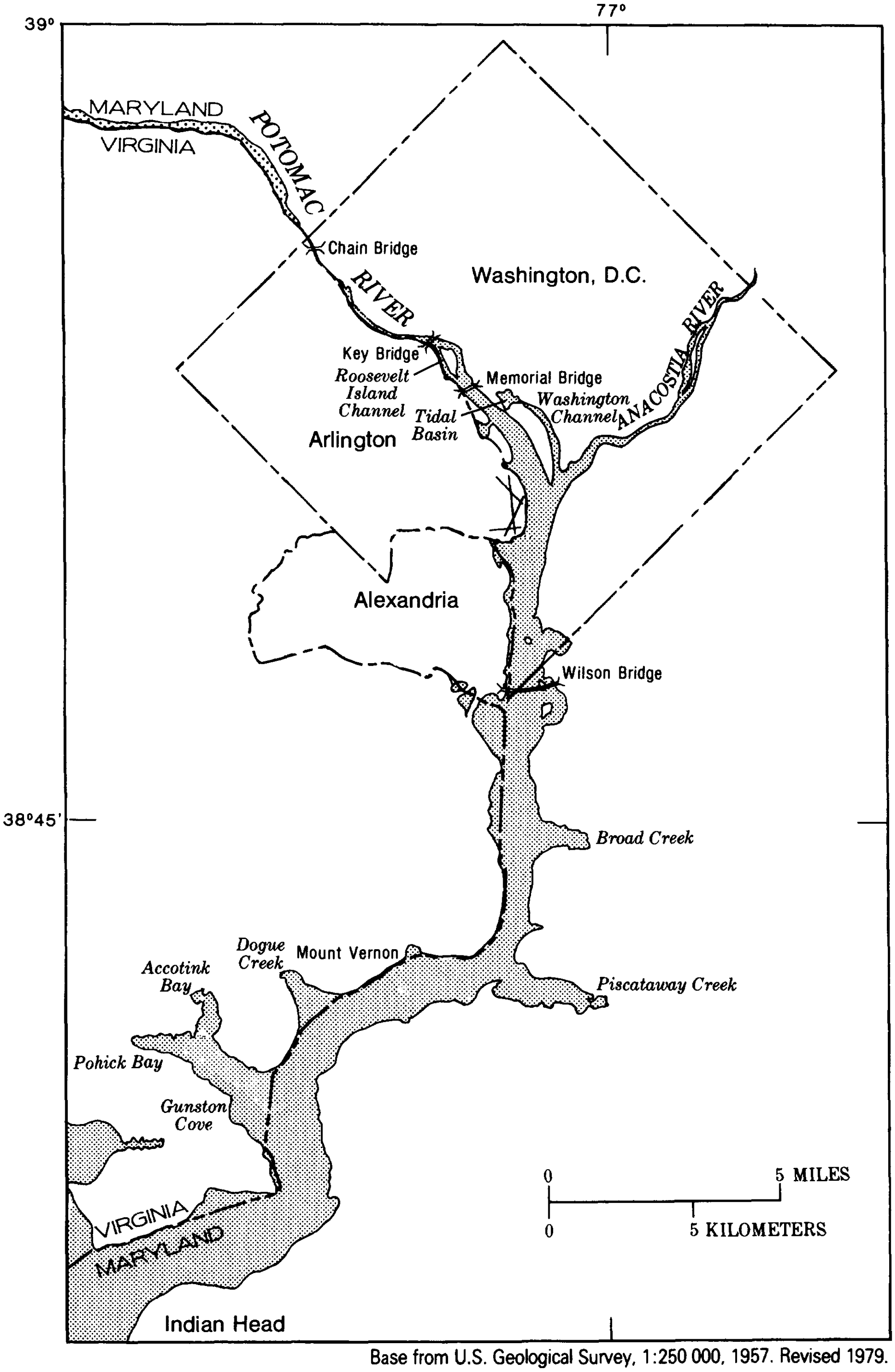


**Figure 1.** Potomac River near Washington, D.C.

3,810 $m^2$ at Wilson Bridge and to 9,960 $m^2$ at Indian Head. The corresponding channel width increases from a minimum of 44.2 m at Chain Bridge to 1,160 m at Wilson Bridge and to 1,950 m at Indian Head. Although the channel bottom is somewhat irregular, with scour-hole depths in excess of 21 m near Piscataway Creek and 24 m immediately upstream of Key Bridge, in general the depth varies from about 9 m at Chain Bridge to about 12 m at Indian Head.

The variable geometry of the tidal Potomac River is illustrated by plots of seven selected cross sections at Chain Bridge, Key Bridge, Daingerfield Island, Wilson Bridge, Hatton Point, Mount Vernon, and Indian Head (fig. 2).

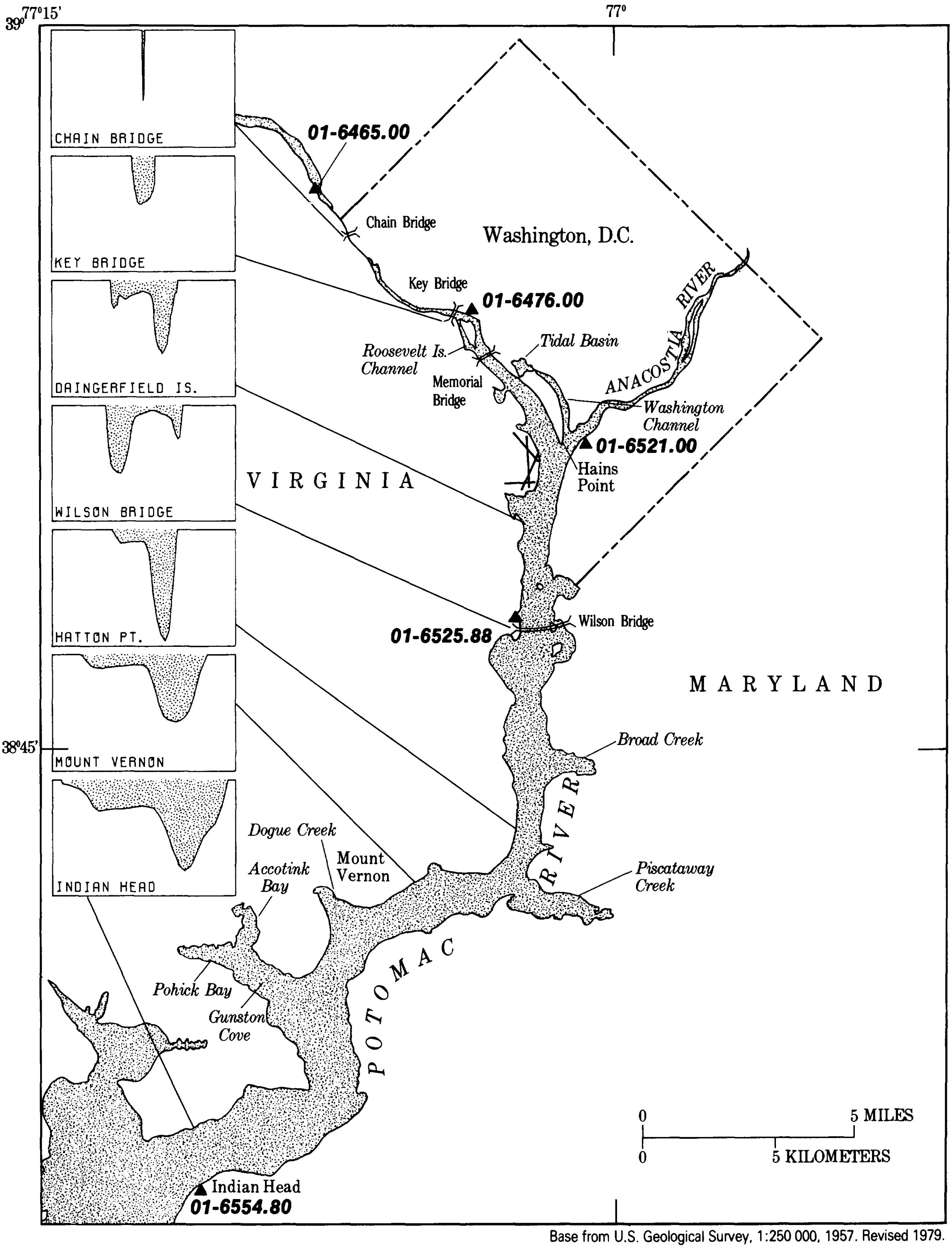


**Figure 2.** The tidal Potomac River system. Numbers in bold are gaging station numbers.

Although the channel geometry is irregular, field investigations confirm that flow in the tidal river consists of predominately longitudinal ebb and flood currents. Semidiurnal tides constitute the flow pattern. The rapid decrease in cross-sectional area with upstream distance contributes to a generally observed amplification of the tide wave as it propagates upstream.

Two distinct flow patterns prevail within the tidal Potomac River—namely, unidirectional pulsating flow and bidirectional flow. The former typically occurs in the narrow channel of the upstream portion of the river, whereas the latter occurs in the broader downstream channel. The location of the transition from one flow pattern to the other varies primarily in response to changing freshwater inflow, as well as to changing tidal and meteorological conditions. For average freshwater inflow (discharge of 325 $m^3/s$ at Chain Bridge) and typical tidal conditions, this transition is usually located in the vicinity of Hains Point where the Anacostia River joins the Potomac. Under conditions of low freshwater inflow (discharge less than 75 $m^3/s$ at Chain Bridge) and typical tidal conditions, the transition can occur as far upstream as Key Bridge. During high freshwater inflow events (discharge greater than 1,000 $m^3/s$ at Chain Bridge) and typical tidal conditions, the transition from unidirectional pulsating to bidirectional flow occurs in the vicinity of, or downstream of, Wilson Bridge, depending upon the magnitude of the inflow. Unusual tidal and meteorological conditions can, of course, alter the location of the flow transition.

## THE BRANCH-NETWORK FLOW MODEL

The flow model of the tidal Potomac River system is as presented in Schaffranek and others (1981). The model is formulated on the one-dimensional version of the full dynamic equations governing unsteady open-channel flow, frequently referred to as the St. Venant equations. Previous, known flow-model applications to the tidal Potomac River have employed one-dimensional link-node type models formulated on simplified versions of the unsteady flow equations. The branch-network model employed in this study not only includes the commonly encountered forcing functions as described by the St. Venant equations but also specifically accounts for flow induced by wind conditions. Wind effects and their subsequent influence on tidal excursions in the river system are illustrated by special-purpose graphical output features of the general flow model that are described in the section "Effects of wind."

The branch-network flow model solves the one-dimensional equations of unsteady flow that consist of the following equations of continuity and of motion:

$$B \frac{\partial Z}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \qquad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial(\beta Q^2/A)}{\partial x} + gA\frac{\partial Z}{\partial x} + \frac{gk}{AR^{4/3}} Q|Q| - \xi B U_a^2 \cos\alpha = 0 \qquad (2)$$

In these equations, water-surface elevation, $Z$, and flow discharge, $Q$, are the dependent variables, and longitudinal distance along the channel, $x$, and time, $t$, are the independent variables. The cross-sectional area, channel top width, gravitational acceleration, lateral inflow, hydraulic radius, and wind velocity occurring at an angle $\alpha$ with respect to the positive x-axis are, respectively, given by $A$, $B$, $g$, $q$, $R$, and $U_a$.

The coefficient $\beta$, known as the momentum or Boussinesq coefficient, can be expressed as

$$\beta = \frac{\int u^2 \, dA}{U^2 A} \qquad (3)$$

It is used to adjust for any nonuniform velocity distribution in the channel cross section. In this expression, $u$ represents the velocity of water passing through some finite elemental area, $dA$, whereas $U$ represents the mean flow velocity in the entire cross-sectional area, $A$.

The coefficient $k$ is a function of the flow-resistance coefficient, $\eta$, (similar to Manning's $n$), which can be expressed as $(\eta/1.49)^2$ in the inch-pound system of units or simply as $\eta^2$ in the metric system.

The coefficient $\xi$ is the dimensionless wind-resistance coefficient, which can be expressed as a function of the water-surface drag coefficient, $C_d$, the water density, $\rho$, and atmospheric density, $\rho_a$, as

$$\xi = C_d \frac{\rho_a}{\rho} \qquad (4)$$

Equations 1 and 2 constitute the basic equations governing one-dimensional unsteady flow in open channels. These equations contain terms that account for the effects of wind forces and lateral inflow. In their derivation, the flow is assumed to be substantially homogeneous in density, and hydrostatic pressure is assumed to prevail at any point in the channel. The channel is assumed to be straight, its geometry simple, and its gradient mild and uniform throughout. Furthermore, frictional resistance is assumed to be amenable to approximation by the Manning formula. The resultant set of nonlinear partial-differential equations defies analytical solution. However, approximate solutions can be obtained by finite-difference techniques such as the one used in the branch-network flow model.

The branch-network flow model employs a weighted, four-point, finite-difference approximation of the nonlinear, partial-differential flow equations. The finite-difference technique is described in detail by Schaffranek and others

(1981). A weighted four-point implicit scheme is used because (1) it can readily be applied with unequal distances between cross sections, (2) it can easily be varied throughout the range of approximation depicted by a box-centered scheme on the one hand to a fully forward scheme on the other, and (3) its stability-convergence properties can be controlled.

To effect a solution by implicit means, the flow equations are first linearized. The equation set is rendered linear by assigning values, initially through extrapolation and subsequently through iteration, to one unknown quantity in those terms involving products of the dependent variables. Iteration serves to diminish any difference between the values used to compute such products. The efficiency of the method is primarily dependent on accuracy of the initial approximation of the unknown variables in the nonlinear terms. In general, the extrapolation procedure has been found to yield sufficiently accurate initial values to assure convergence of the solution within one to three iterations.

After the flow equations for all segments—a segment being the primary subdivision of a channel—within the network are developed by the model and appropriate boundary conditions are defined by the user, a system of equations is formed that is determinate. This linear equation set is directly solvable by matrix methods once appropriate coefficient matrices are constructed. In the branch-network model formulation, however, transformation equations that relate the unknowns at the ends of the channels of the network (herein referred to as branches) are developed within the model from the segment flow equations. These branch-transformation equations are used in place of the segment flow equations to develop the coefficient matrices. The reason for using branch-transformation equations instead of segment flow equations is a resultant dramatic reduction in computer memory and execution time requirements. After initial solution of the branch-transformation equations produces the unknown water-surface elevations and discharges at the ends of the branches of the network, intermediate values of the unknowns at the ends of the segments are derived by the model through back substitution. Details on the equation transformation technique are presented by Schaffranek and others (1981).

## MODEL DEVELOPMENT

Implementation of the branch-network flow model to the tidal Potomac River system was accomplished in three distinct phases. The initial phase was application of the model to the upstream 19.7-km portion of the tidal river from Chain Bridge to Wilson Bridge. This subset model included the Anacostia River, Roosevelt Island Channel, Washington Channel, and the Tidal Basin (Schaffranek and Baltzer, 1980). The second phase of model implementation involved application of the model to the downstream 30.1-km portion of the tidal river from Wilson Bridge to Indian Head, Md. This subset model included the Broad Creek, Piscataway Creek, Dogue Creek, Gunston Cove, Pohick Bay, and Accotink Bay tidal inlets. In the final phase of model development, these two subset models were combined to form a complete model of the 49.8-km tidal Potomac River, including its major side-channel tributaries and tidal embayments (Schaffranek, 1982).

### Network Schematization

A schematic of the modeled river system is shown in figure 3. The network is composed of 25 branches (identified by Roman numerals) that either join and (or) terminate at 25 junction locations (identified by numbered boxes). Junction 8 of the network schematization represents the head-of-tide for the Anacostia River. As indicated by junction 13 (representing the upstream end of Washington Channel) and junction 14 (representing the upstream end of the Tidal Basin), no flow exchange is permitted between the Tidal Basin and Washington Channel by the model. As figure 3 illustrates, flow around the west side of Roosevelt Island is accommodated within the model by branch 19. The Broad Creek, Piscataway Creek, Dogue Creek, Gunston Cove, Pohick Bay, and Accotink Bay tidal inlets also are included in the network schematization (see fig. 3). Those junctions that do not constitute tributary or inlet locations in figure 3 were deemed necessary in the network schematization to accommodate potential nodal flows (point source inflows or outflows such as sewage treatment outfalls or pump withdrawals) or abrupt changes in channel characteristics.

### Channel Geometry

Cross-sectional profiles of the channels were required at all junction locations and, in addition, at selected locations between junctions to properly depict channel irregularities. A total of 66 cross sections located at unequal intervals along the channels was used to depict the irregular geometry of the 25-branch network. After the cross-section locations were established, segment lengths required by the model were determined by measuring distances between cross sections along the thalwegs of the channels as interpolated from hydrographic charts. Orientations of the channel segments with respect to true north also were determined from these hydrographic charts to permit model evaluation of wind influences.

Hydrographic data consisting of over 40,000 depth soundings were obtained from the National Ocean Survey, National Oceanic and Atmospheric Administration (NOS/NOAA), to develop the cross-sectional profiles. From this set of data, soundings within a narrow envelope of influence surrounding each cross-section location were selected and

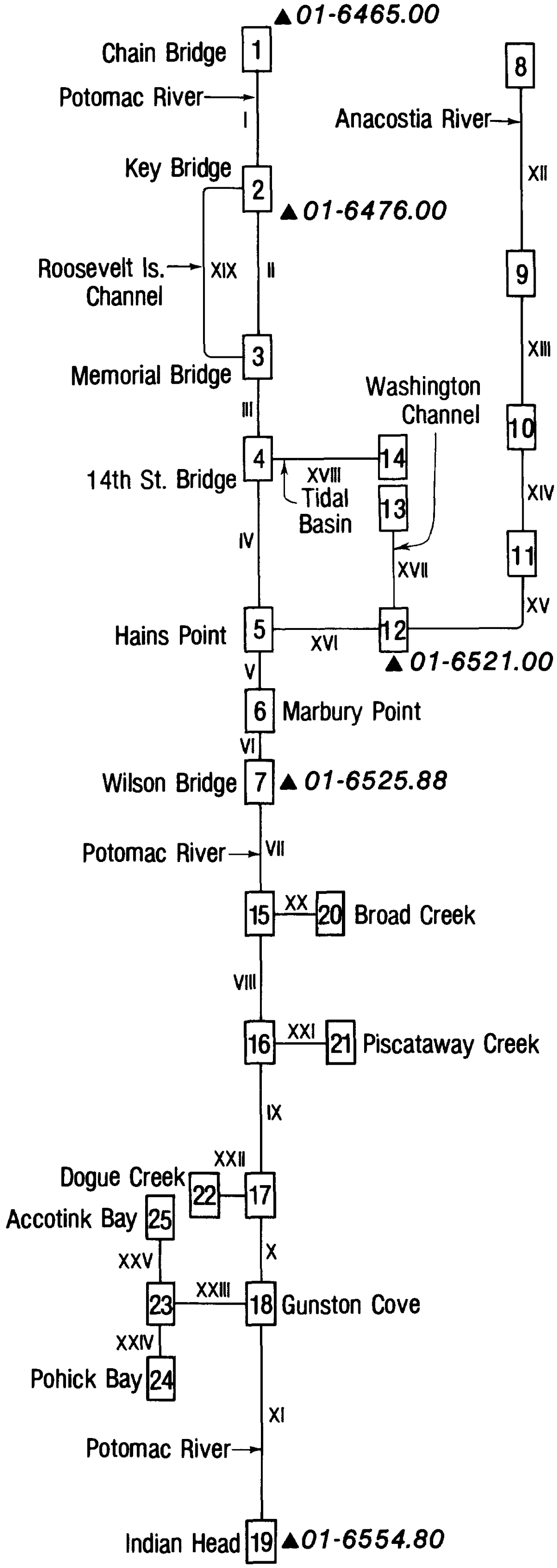


**Figure 3.** Schematic diagram of the tidal Potomac River system for the branch-network flow model.

used to derive, through polynomial surface interpolation, the needed cross-sectional properties.

Cross-section locations were chosen to accurately characterize the channel geometry of the network for model development. Of the 66 cross-sectional profiles, 28 were used to describe the geometry of the tidal Potomac River itself. The remaining 38 were used to describe the geometry of the other channels of the network. Segment lengths (intervals between cross-section locations) range from 0.71 to 4.82 km.

## Boundary Conditions

Like most unsteady flow models, the branch-network model requires that one of the time-dependent variables—either the water-surface elevation or flow discharge—be known throughout time at the physical extremities of the network being simulated. As can be seen from the network schematization of figure 3, boundary conditions must be specified for the tidal Potomac River flow model at Chain Bridge (junction 1) and Indian Head (junction 19), as well as for the Anacostia River (junction 8) and for junction locations 13, 14, 20, 21, 22, 24, and 25. Typically, sequences of discrete water-surface elevations are recorded at such locations and supplied to the model to satisfy these boundary condition requirements. However, flux rates (discharges) can also be, and commonly are, used as boundary-value data—for example, the null discharge at the closed end of a dead-end channel.

The tidal Potomac River flow model uses discharges derived from a rating curve for a gaging station (station number 01–6465.00 in fig. 2), 1.9 km upstream from Chain Bridge, as boundary-value data at junction 1. Water-surface elevations continuously recorded at a gaging station (station number 01–6554.80 in fig. 2) at Indian Head, Md., are used as boundary-value data at junction 19. All other external boundary conditions, including the Anacostia River, are fulfilled by assuming that zero discharge conditions prevail at the upstream tidal extent of the channel or embayment. Of course, if inflow rates or water-surface elevations were known at any of these locations they could be supplied to the model as boundary values for making flow simulations.

The model also requires boundary conditions at internal junctions of the network. The model automatically generates equations based on discharge continuity and stage-compatibility conditions that constitute consistently prevailing conditions at these locations (see Schaffranek and others, 1981). By neglecting velocity differences and energy losses due to turbulence at these junctions, such boundary conditions can be appropriately specified. The discharge-continuity condition simply requires that the sum of the discharges into and out of a junction be equal to the specified external nodal flow at the junction. The stage compatibility condition requires that the water-surface elevation be single valued at the internal junction.

Effluent discharge from the Blue Plains sewage treatment plant located near Marbury Point in the southeastern quadrant of the District of Columbia, approximately 2.25 km upstream of Wilson Bridge, is treated by the model as nodal inflow at junction 6. This is necessary to satisfy the discharge-continuity condition at this internal junction.

### Initial Conditions

Although the resultant set of flow equations, internal boundary condition equations, and external boundary conditions expressed in equation form are sufficient to make the system of equations determinant, initial values for the unknown quantities are required to start the solution process. These values may be obtained from measurements computed from some other source such as steady-state approximations, computed from previous simulations, or otherwise estimated. The model's successive use of newly computed values as initial values permits the computation to proceed step-by-step at the specified computation time interval until the simulation is completed. The required initial conditions for the tidal Potomac River flow-model simulations, illustrated herein, were derived from previous simulations.

## MODEL CALIBRATION AND VERIFICATION

Calibration and verification of a model is a necessary, preliminary task to be performed prior to its operational use. Model calibration is the process by which adjustments are made to coefficients and parameters used by the model with the objective being to minimize differences between measured data and model-computed values. Subsequent verification runs substantiate the credibility of the calibration results.

Model calibration and verification are separate processes. This distinction is important. The necessity to verify that calibrated model coefficient and parameter values are valid for other flows under similar conditions must be recognized. It is then, and only then, that a model can be considered calibrated.

An equally important aspect of model calibration and verification is a full understanding of the manner and degree to which a change in a given coefficient or parameter affects the computed results. Such sensitivity analysis should be performed early to identify those coefficients and parameters most sensitive and requiring the most attention in the calibration and verification processes. Such an analysis also can be useful in defining the degree of allowable adjustment to the applicable coefficients and parameters in order that the values assigned be physically realistic.

Just as implementation of the branch-network flow model to the tidal Potomac River was accomplished in distinct phases, so too were model calibration, verification, and sensitivity analyses conducted. Initially, calibration and sensitivity tests were performed for the model of the upstream portion of the tidal river from Chain Bridge to Wilson Bridge. Next, similar tests were conducted for the model of the downstream portion of the tidal river from Wilson Bridge to Indian Head, Md. The final phase of model calibration and verification involved testing the complete model of the tidal river from Chain Bridge to Indian Head, Md., including its major side-channel tributaries and tidal embayments. By subdividing the system into smaller subset models, model calibration was accomplished more systematically and, therefore, more economically.

### Source and Accuracy of Measured Data

Data for model calibration and verification typically consist of discharges measured over continuous periods of time, together with concurrent water-surface elevations. The water-surface elevations, continuously recorded near Key Bridge (station number 01–6476.00 in fig. 2), near Hains Point (station number 01–6521.00 in fig. 2), and near Wilson Bridge (station number 01–6525.88 in fig. 2), were used to calibrate and subsequently verify the model. Discharge data used in model calibration and verification were obtained from measurements conducted for complete tidal-cycle durations near National Airport (at the Daingerfield Island cross-section location shown in fig. 2), near Broad Creek (at the Hatton Point cross-section location shown in fig. 2), and at Indian Head (at the cross-section location shown in fig. 2). These tidal-cycle discharge measurements were also augmented, and in some instances extended in duration, by correlation with speed and direction-of-flow data obtained from concurrently operated, automatic, self-recording current meters moored at selected locations throughout the network of channels. In all, five tidal-cycle discharge measurements were made to provide data for calibrating and subsequently verifying the model. Two measurements were made near Broad Creek, two were made at Indian Head, and a fifth and final one was made near National Airport. These measurements, made with multiple boats and measuring crews, were manpower- and equipment-intensive operations. Measurement sites were chosen so as to provide discharges of a high level of accuracy at locations deemed critical to model calibration. In general, measurement times were chosen on the basis of favorable weather conditions and with the aim of personnel safety in mind. Model-computed results are compared with these measured data in a subsequent section of this report.

## Computation-Control Parameters

Before flow simulations could be made with the tidal Potomac River flow model, several parameters that principally control the numerical simulation process had to be evaluated. Three factors critical with regard to controlling the numerical computation are the simulation time increment, appropriate finite-difference weighting factors, and valid convergence criteria. The simulation time increment is the interval at which successive solutions of the flow equations are sought. The finite-difference weighting factors define the structure of the finite-difference approximation of the flow equations. User-defined convergence criteria control the accuracy of the approximated solutions. Details on these computation-control parameters are given in Schaffranek and others (1981). In the tidal Potomac River model calibration process, it was determined that the flow simulations ought to be made with a 15-minute time step, a value of 0.6 for the weighting factor for the spatial derivatives, and a value of 0.5 for the weighting factor for functional quantities. For these time step and weight factor assignments, flow simulations have satisfied convergence criteria set at 0.0046 m and 0.71 $m^3/s$ for water-surface elevation and discharge, respectively, in less than three iterations per time step, on the average. These specifications of the primary computation-control parameters have been verified for flow simulations made with the model.

## Flow-Conveyance Parameters

In addition to computation-control parameters, certain other parameters must be defined. These principally describe the conveyance properties of the channels. Although these parameters cannot be measured directly, they can be derived from certain measured data. They depend principally upon the physical properties of the channels, but also, to a lesser degree, on the schematization of the channel geometry and on any inherent minor inaccuracies therein. Consequently, the values of these parameters may require adjustment and refinement throughout the model calibration process. Even though they are subject to adjustment in the model calibration process, their values should not exceed the expected limits as derived through specific field observations, or as otherwise determined.

Specifically, the flow-conveyance parameters are determined by the flow-resistance coefficient, the velocity-distribution (momentum) coefficient, and the wind-shear, water-surface drag coefficient. Accurate definition of the flow-resistance coefficient is always required. Evaluation of the momentum coefficient may be required for flow conditions in which the velocity distribution is highly nonuniform throughout the cross section. The wind-shear, water-surface drag coefficient is required under severe wind conditions whenever it is necessary to account for wind-induced currents caused by wind stress acting on the water surface within the channels of the network.

Of the flow-conveyance parameters identified, perhaps the most difficult to quantify is the flow-resistance coefficient. This is particularly true because the flow-resistance coefficient typically is a compound function of the physical and hydraulic properties of the channel. Flow-resistance coefficients typically are initially estimated and subsequently adjusted during model calibration to produce agreement between measured data and model-computed results.

Calibration of the tidal Potomac River flow model has resulted in flow-resistance coefficient values ranging from 0.0275 at Chain Bridge to 0.019 at Indian Head for the Potomac River itself. Coefficient values for all other flow segments within the network likewise fall within this range. This range of coefficient values appears to be reasonable and consistent with the properties of the channels. Irregularities in the channel bottom formation and in the bottom materials primarily influence the shape of the velocity distribution near the bottom and, therefore, also affect the mean velocity. The chosen flow-resistance coefficient values must, therefore, be reasonable in terms of the channel bottom properties. In the upstream portion of the tidal Potomac River, the channel bottom consists of rocks and large boulders and, in general, is considerably more irregular in configuration than the downstream portion of the tidal river that consists of both coarse- and fine-grained bottom material. Consequently, the determined flow-resistance coefficient values that gradually decrease downstream appear to be consistent with the properties of the channel, and, to the extent possible, this trend has been confirmed through observations. Throughout the calibration process, the flow-resistance coefficient values were adjusted from their initially estimated values until satisfactory agreement was achieved between computed and measured flow data.

The velocity-distribution coefficient is a numerical measure of the departure of the velocity from a uniform distribution throughout the cross section. A value of one implies a precisely uniform velocity distribution, ideally in direct concurrence with the mean velocity for the cross-sectional area computed by a one-dimensional flow model. In reality, such a uniform velocity distribution never occurs because of channel contractions and (or) expansions, channel meanders, or cross-sectional irregularities such as islands, sandbars, or gullies. For the turbulent flows typical of most natural channels, the velocity-distribution coefficient is on the order of 1.06 (Chow, 1959). This value for the velocity-distribution coefficient has been used in the flow simulations made with the tidal Potomac River flow model.

Determination of the wind-shear, water-surface drag coefficient is necessary whenever flow conditions are affected by wind-induced currents caused by wind stress acting on the water surface within the channels of the network. Experimentation has shown that the value of this coefficient depends not only on the flow depth but also on the height, steepness, and celerity of the wind-generated surface waves. Representative values of the water-surface drag coefficient appear to range between suggested values of $1.5 \times 10^{-3}$ for light winds and $2.6 \times 10^{-3}$ for strong winds (Wilson, 1960). For the flow simulations made with the tidal Potomac River flow model, a value of $1.5 \times 10^{-3}$ has been found to be most suitable for the water-surface drag coefficient.

## Simulation Results

Numerous flow simulations were made during model calibration and verification. The previously identified computation-control and flow-conveyance values were those finally determined to be appropriate in the model calibration process. This conclusion was based on comparisons of model-computed results with the aforementioned measured data. Details of the parameter-evaluation effort are not presented herein; however, comparisons of measured data and simulated results produced with the specified parameter assignments are illustrated in figures 4 and 5. These comparisons of model-computed results with recorded water-surface elevations and measured tidal-cycle discharges are intended to illustrate the present level of model calibration. Certainly additional refinement can be achieved; some areas that may require review are identified subsequently.

In figure 4, model-computed water-surface elevations (stages) are shown plotted against water-surface elevations recorded at various locations during the time interval of the aforementioned five tidal-cycle discharge measurements. Computed water-surface elevations are plotted against values recorded at the measurement location for the March 10 and 12, 1981, Broad Creek measurements and for the September 14, 1981, National Airport measurement in figures 4*A*, *B*, and *E*. For the May 13, 1981, Indian Head measurement, water-surface elevations computed and recorded near Hains Point (station number 01–6521.00 in fig. 2) are plotted in figure 4*C*. For the June 3-4, 1981, Indian Head measurement, water-surface elevations computed and recorded near Key Bridge (station number 01–6476.00 in fig. 2) are plotted in figure 4*D*. Comparison of water-surface elevations at locations other than Indian Head for these two measurements is both necessary and desirable. Water-surface elevations recorded at the Indian Head measurement location are used as boundary values for the flow simulations, therefore, a more rigorous evaluation of model performance results from comparisons of water-surface elevations at alternative locations. Such comparisons also illustrate the accuracy with which the model simulates wave propagation through the channel system.

The comparisons of computed and recorded water-surface elevations in figure 4 are presented only to illustrate the model's present level of accuracy. No attempts were made in these specific flow simulations to improve the comparison between computed and recorded water-surface elevations. (Preliminary model calibration using water-surface elevations was undertaken in flow simulations of the subset models in which data from other time periods were used.) As the comparisons of figure 4 indicate, some degree of improvement in the model's computation of water-surface elevations is needed, particularly during the recession of the tide from high to low slack. The noted disparity also appears to increase somewhat for lower low tides, as indicated by figures 4*B* and *C*. Such discrepancies may be able to be resolved in subsequent model refinement. However, any attempt to improve upon these water-surface-elevation comparisons must logically be constrained by the desire to have favorable comparison between computed and measured discharges, as well as between measured and computed tidal-cycle volume fluxes, as described below.

Model-computed discharges are plotted against tidal-cycle discharges measured near Broad Creek on March 10 and 12, at Indian Head on May 13 and June 3–4, and near National Airport on September 14, 1981, in figure 5. Model calibration was accomplished with the three sets of discharge data measured near Broad Creek on March 12, at Indian Head on June 3–4, and near National Airport on September 14. The remaining two sets of discharge data measured near Broad Creek on March 10 and at Indian Head on May 13 were used primarily to verify the model calibration by evaluating its performance under different boundary-value data conditions. Overall the comparisons of computed and measured hydrographs for the five time periods shown in figure 5 appear to be reasonably good. The best agreement is evidenced by the June 3–4 hydrographs in figure 5*D* whereas the March 10 and 12 hydrographs in figures 5*A* and *B* exhibit perhaps the poorest comparisons. Coincidently, independent qualitative assessments of the tidal-cycle discharge measurements rated the June 3–4 measurement as the best and the March measurements as the poorest. (During the March measurements, strong winds produced highly unfavorable measuring conditions. In particular, winds during the receding part of the flood tide were quite troublesome.) The noted discrepancies during the ebb tides coincide with the lack of agreement between computed and recorded water-surface elevations during the recession of the tide from high to low slack. Consequently, it would seem that attempts to improve upon the model's computation of water-surface elevations during these periods would also serve to diminish the noted discharge differences. Additional calibration tests are needed to verify the model's performance during these phases of the tidal cycle.

Although the comparison plots of figure 5 permit a visual qualitative assessment of model calibration, a more rigorous quantitative evaluation is desirable. Such a comprehensive evaluation can be made by comparing computed and measured volume fluxes through the measurement cross sections on successive ebb and flood cycles of the tide.

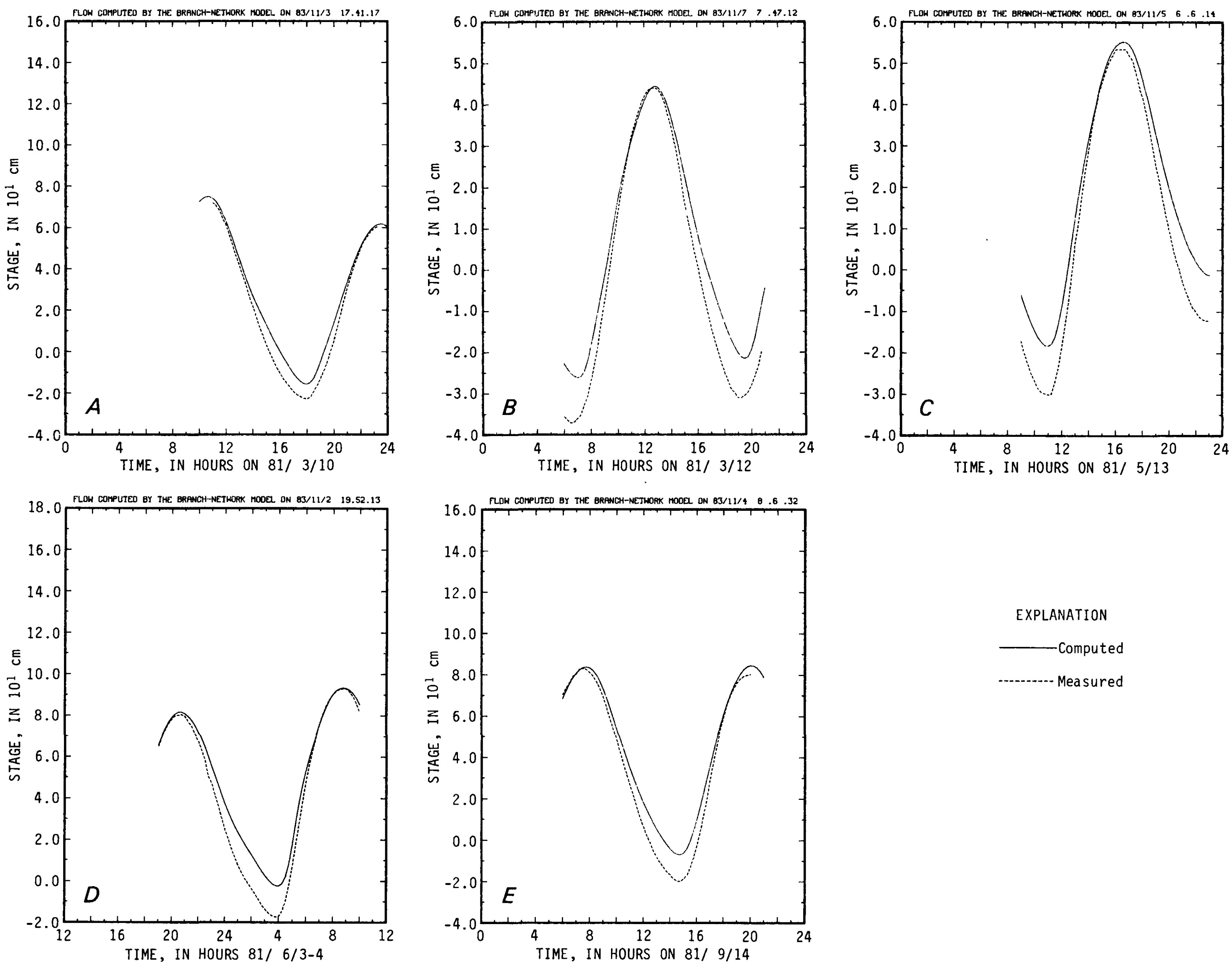


**Figure 4.** Model-generated plots of computed (solid line) versus measured (dotted line) water-surface elevations for the Potomac River near Broad Creek (*A*, *B*), near Hains Point (*C*), near Key Bridge (*D*), and near National Airport (*E*).

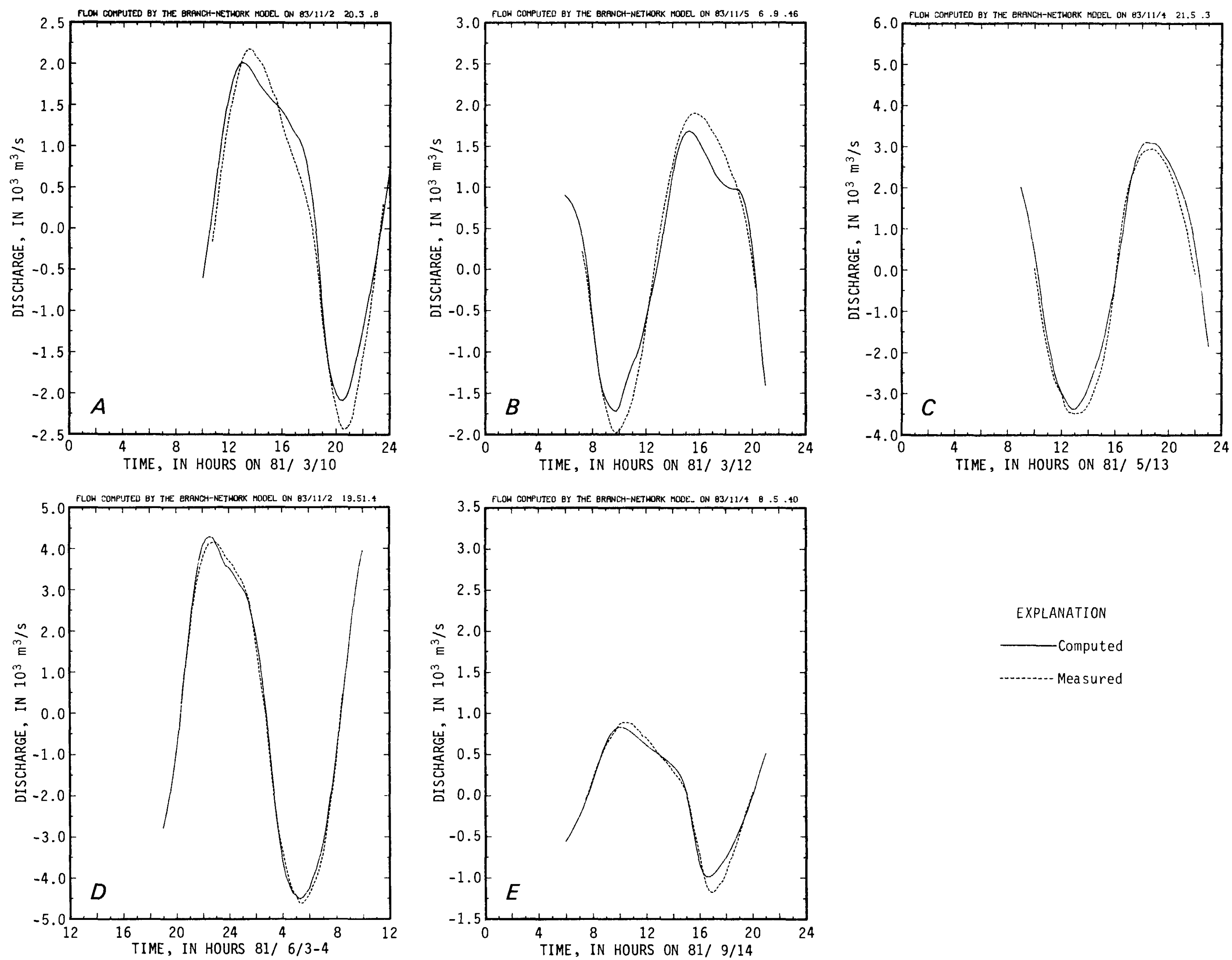


**Figure 5.** Model-generated plots of computed (solid line) versus measured (dotted line) discharges for the Potomac River near Broad Creek (*A, B*), at Indian Head (*C, D*), and near National Airport (*E*).

Knowledge of model credibility in accurately computing such mass transport is particularly important if model-computed flows are to be used, for instance, for determining sediment and nutrient fluxes and loads. Computed and measured flood (negative) and ebb (positive) volume fluxes for the five tidal-cycle discharge measurements are given in table 1.[1] Also provided in table 1 are assessments of the quality of the individual measurements, pertinent wind and inflow conditions during the measurements, and the difference between computed and measured flow volumes. As noted in the previous discussion, the best comparisons are for the measurements judged to have yielded the most accurate data, namely, the June 3-4 Indian Head and September 14, 1981, National Airport measurements. Based on the quality of these comparisons, it would seem justified to conclude that such flow volumes can be computed by the model to within an accuracy of ±10 percent.

## Sensitivity Analyses

An important aspect of model calibration and verification is the performance of an exhaustive and comprehensive analysis of model coefficient and parameter sensitivity. The purposes of such an analysis are primarily threefold. First, a full understanding of the manner and degree to which a change in a given model coefficient or parameter affects the computational results is vital to assure that selected values are physically and (or) mathematically realistic for the flow conditions being simulated. Model computed flows can be, and typically are, significantly influenced by coefficient and parameter values assigned to effect solutions of the system of flow and boundary-condition equations. Therefore, gaining insight into the individual influence of a given coefficient or parameter on the flow computation is desirable. This aspect of a model sensitivity analysis is also useful in that the most sensitive coefficients and parameters, those requiring the most attention in the calibration and verification processes, are readily identified. A second, equally important, purpose for conducting a model sensitivity analysis is the need to identify the valid range of variability for those coefficients and parameters subject to variation in subsequent flow simulations. A change in a given model coefficient or parameter may necessitate the reevaluation of one or more others. A thorough analysis of the model's performance under various combinations of coefficient and parameter values will provide constraining guidelines for its operational use within the calibration range. A third reason for performing model sensitivity tests is to provide information concerning acceptable error bounds for directly measurable or otherwise quantifiable coefficients and parameters.

[1]Flood volume is the total quantity of water that flows upstream in the time period between the slack waters of successive ebb and flood tides; similarly ebb volume is the total quantity of reciprocal downstream flow.

Boundary-value and initial-condition data are two examples of required data whose validity may be questionable due to measurement error (boundary conditions) or inaccurate estimation (initial conditions). Flow computations performed with such data may yield results that are of questionable validity, even though the model may have remained stable and convergent throughout the simulated time period.

Sensitivity analyses for the tidal Potomac River flow model were initially conducted for the subset models of the upper and lower portions of the tidal river system. Subsequent tests with the complete model of the tidal river, including its major side-channel tributaries and tidal embayments, were performed during various phases of model calibration and verification. The results of these sensitivity tests are not shown herein. However, the results of model sensitivity tests performed with the calibrated model are shown to provide guidelines for its operational use. These sensitivity analyses were conducted with various computation-control parameter values, boundary-value data adjustments, and initial-value data estimates. They are intended to illustrate the significance of changes and (or) errors in coefficients and parameters critical to the flow-simulation process.

### Computation Control

For a given simulation, varying one or more computation-control parameters—that is, the simulation time increment, the spatial derivative weighting factor, and the computation convergence criteria—may be desirable. A typical alternative may be to have the model compute flow information at other than the recommended 15-minute time step. To illustrate the effects of running the model at both a larger and smaller time step, two simulations were made—one using a 5-minute time step and a second with a 60-minute time step. Discharge hydrographs derived from the simulations are shown plotted in figure 6. Also plotted in figure 6 are discharges computed at Indian Head on June 3-4, using a 15-minute time step. The results of these three simulations are summarized in table 2. For these simulations—identified as run numbers 1, 2, and 3 in table 2—the spatial-derivative weighting factor ($\theta$) and the computation convergence criteria, as well as the maximum iterations allowed per time step, were held constant. As expected, the number of solutions and the computer time decreased and increased, respectively, for the flow simulations performed with a 60-minute time step (run number 2) and a 5-minute time step (run number 3). Both simulation runs, however, required a greater number of solutions per time step to satisfy the specified computation convergence criteria. Each of the simulations performed with larger and smaller time steps required, on the average, one or more additional solutions per time step than the three solutions required for the computation performed at a 15-minute time step. Although a significant savings in computer time is evident from comparison of the Central Processing Unit

**Table 1.** Comparison of computed and measured flow volumes

| Measurement | | | Wind conditions | Average inflow | Ebb volume | | | Flood volume | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | Location | Rating | (kph) | ($m^3$/s) | Measured ($10^7$ $m^3$) | Computed ($10^7$ $m^3$) | Diff. (%) | Measured ($10^7$ $m^3$) | Computed ($10^7$ $m^3$) | Diff. (%) |
| 3/10/81 ----- | Hatton Point | Poor | 3–20 NW | 230 | 3.53 | 3.87 | 9.7 | −2.72 | −2.29 | −15.7 |
| 3/12/81 ----- | Hatton Point | Fair | 6–26 W | 220 | 3.41 | 2.90 | −15.0 | −2.32 | −1.99 | −14.4 |
| 5/13/81 ----- | Indian Head | Fair | 3–11 SW | 290 | 4.28 | 4.69 | 9.5 | −5.29 | −4.70 | −11.1 |
| 6/3-4/81 ---- | Indian Head | Good | 1–12 SW | 365 | 6.66 | 6.70 | 0.6 | −6.26 | −6.11 | −2.4 |
| 9/14/81 ----- | Natl. Airpt. | Good | 3–7 SW | 75 | 1.45 | 1.41 | −3.0 | −1.22 | −1.09 | −10.6 |

(CPU) time for run numbers 1 and 2, the quality, and therefore the usefulness, of the results computed with a 60-minute time step may be subject to question (see fig. 6). The discharge hydrograph computed by use of a 60-minute time step presents a poor approximation of the flow conditions by comparison with the results computed with a 15-minute time step. An interesting aspect of the computation performed at the 5-minute time step is shown by the computed discharge hydrograph also plotted in figure 6. Fluctuations in the discharge hydrograph are noticeable at approximately 0600 hours on June 4. These fluctuations stem directly from the model's inability to satisfy the specified convergence criteria during these time steps. The branch-network flow model is programmed to attempt to continue the simulation in spite of not having satisfied the specified convergence criteria in the allowed number of iterations. In doing so, the model assumes that the last computed values are valid and attempts to proceed with the rest of the simulation. In general, the model will recover, converge again to a solution, and successfully complete the entire simulation. Such fluctuations, however, are cause for concern. Frequently, they are indicative of boundary-condition errors, although—as is the case for this particular simulation—they may be caused by other factors. It commonly is a natural reaction of the modeler upon encountering such fluctuations to "loosen up" the computation convergence criteria and repeat the simulation. This practice, however, is not recommended and generally will not produce significantly improved results. As an example to illustrate this point, an attempt was made to repeat the simulation with a 5-minute time step and a value of 2.1 $m^3$/s for the discharge convergence criterion. This attempt failed, as the fluctuations grew too large to permit the model to continue the simulation.

Two additional simulations were made with a 5-minute time step to determine the influence of the spatial derivative weighting factor ($\theta$) on the flow computation. These simulations were made to determine if a suitable weighting factor could be determined that would produce a discharge hydrograph free of the fluctuations shown in figure 6. The results of these simulations, in which values of 0.75 and 1.0 were used for $\theta$, are summarized as run numbers 4 and 5, respectively, in table 2. As these results indicate, the simulation with a 0.75 value for the spatial-derivative weighting factor required an even greater number of solutions than run number 3 in which a $\theta$ value of 0.6 value was used. Run number 5, in which a $\theta$ value of 1.0 was used, however, indicates a dramatic reduction in the

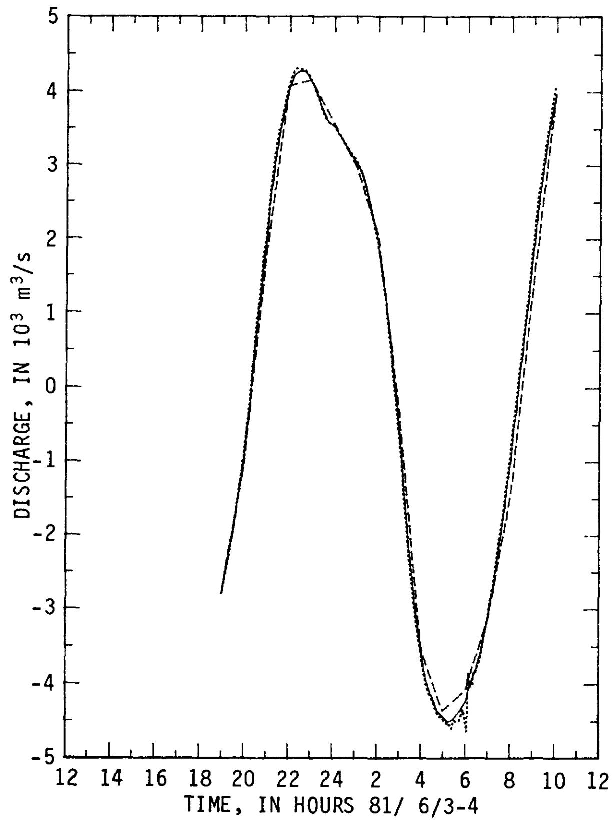


**Figure 6.** Discharges computed for the Potomac River at Indian Head by use of 5- (dotted line), 15- (solid line), and 60- (dashed line) minute time steps ($\Delta t$).

Table 2. Model performance using alternative computation-control parameter values

| Run number | Time step (min) | θ | Maximum iterations | Discharge tolerance (m³/s) | Stage tolerance (cm) | Solutions | CPU (s) | Solutions per time step |
|---|---|---|---|---|---|---|---|---|
| 1 | 15 | 0.6 | 5 | 0.7 | 0.46 | 179 | 16 | 3.0 |
| 2 | 60 | 0.6 | 5 | 0.7 | 0.46 | 65 | 6 | 4.3 |
| 3 | 5 | 0.6 | 5 | 0.7 | 0.46 | 725 | 52 | 4.0 |
| 4 | 5 | 0.75 | 5 | 0.7 | 0.46 | 748 | 54 | 4.2 |
| 5 | 5 | 1.0 | 5 | 0.7 | 0.46 | 437 | 34 | 2.4 |
| 6 | 15 | 0.6 | 1 | 0.7 | 0.46 | 60 | 6 | 1.0 |
| 7 | 15 | 0.6 | 2 | 0.7 | 0.46 | 120 | 9 | 2.0 |
| 8 | 15 | 0.6 | 5 | 3.5 | 0.46 | 147 | 11 | 2.5 |
| 9 | 15 | 0.6 | 5 | 7.0 | 0.46 | 134 | 10 | 2.2 |

number of solutions required to complete the simulation. In fact, the number of solutions required per time step is even less than the number required to satisfy the same convergence criteria with a 15-minute time step. The discharge hydrographs produced with values of 0.75 and 1.0 for the spatial-derivative weighting factor are shown in figure 7 along with the results computed in run number 3 in which a θ value of 0.6 was used. Although the run with a θ value of 0.75 encountered no difficulties in the simulation at 0600 on June 4, fluctuations of an even greater magnitude are evident in the hydrograph at approximately 2200 hours on June 3. Here again, the model was able to recover from the fluctuations and complete the simulation; however, the results are not completely useful. By contrast, the hydrograph computed with a θ value of 1.0 exhibits no fluctuations. The only significant difference apparent in the results of this simulation and of run number 3—aside from the missing fluctuations—is that the magnitude of the maximum ebb and flood discharges is somewhat diminished. Thus, it would seem necessary either to use a θ value of 1.0 or to conduct additional sensitivity tests to arrive at a more appropriate θ value—likely between 0.75 and 1.0—to conduct flow simulations with the tidal Potomac River flow model using a 5-minute time step.

Four additional simulations were performed (the results of which are summarized as run numbers 6 through 9 in table 2) to determine the model's sensitivity to alternative specifications of the maximum iterations allowed per time step and the computation convergence criteria.[2] In runs number 6 and 7, the maximum allowable iterations were set to 1 and 2, respectively, thus forcing the model to proceed with the simulation even though the specified convergence criteria may not have been satisfied. As anticipated, the CPU time required to complete these simulations is dramatically reduced over run number 1 in which three solutions were required per time step. Plots of the discharge hydro-

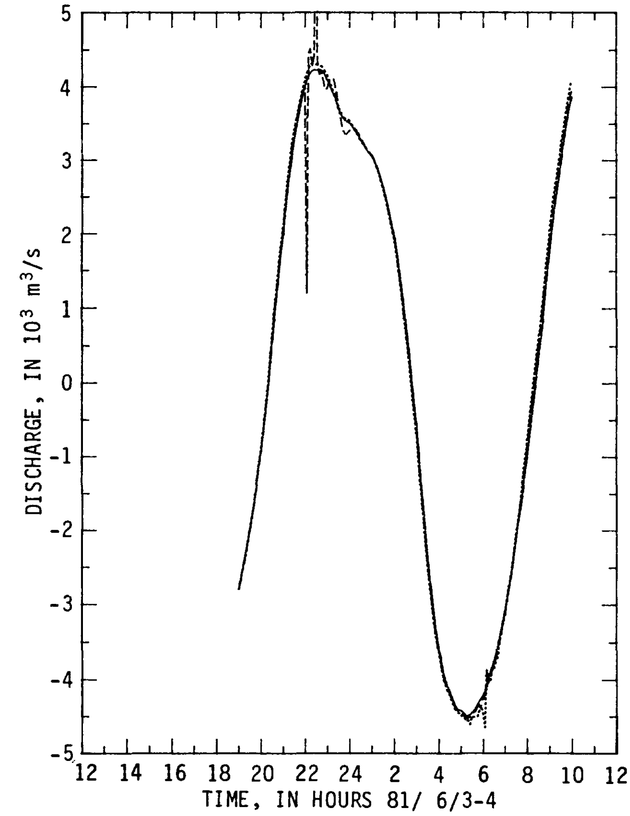


Figure 7. Discharges computed for the Potomac River at Indian Head by use of 0.6 (dotted line), 0.75 (dashed line), and 1.0 (solid line) values for the spatial derivative weighting factor (θ).

[2]Note that these four simulations were performed with the recommended 15-minute time step and a θ value of 0.6.

graphs at Indian Head for these two simulations, although not included herein, show the results to be visually indistinguishable. By comparison with run number 1, run number 6 (1 iteration) yields a mean difference of 8.61 $m^3/s$ and a maximum difference for any given time step of 28.8 $m^3/s$. Run number 7 (2 iterations) yields a mean difference of 0.65 $m^3/s$ and a maximum difference of 2.3 $m^3/s$. For runs number 8 and 9, the maximum number of iterations allowed per time step was again set to the recommended value of 5, and the discharge convergence criterion was set at 3.5 and 7.0 $m^3/s$, respectively. By comparison with run number 1, run number 8, which required approximately 2.5 solutions per time step, yields a mean difference of 0.10 $m^3/s$ and a maximum difference of 0.4 $m^3/s$. Run number 9 yields a mean difference of 0.24 $m^3/s$ and a maximum difference of 0.8 $m^3/s$, while requiring approximately 2.2 solutions per time step. The conclusion to be drawn from these simulations is that the recommended discharge convergence criterion of 0.7 $m^3/s$ might be unnecessarily restrictive, at least for this combination of time step and weighting factor. A less conservative value for the discharge-convergence criterion—on the order of 3.5 $m^3/s$—might be more appropriate when using a 15-minute time step and 0.6 spatial derivative-weighting factor. This value would seem to represent a realistic compromise for reducing the CPU requirements while maintaining an acceptable level of accuracy in the computed flow results. In general, experimentation with the branch-network flow model has shown that, on the average, computation convergence criteria should be satisfied in two to three solutions per time step.

As these simulations have indicated, the branch-network flow model of the tidal Potomac River system is sensitive to alternative settings of the computation-control parameters. As was evidenced by the simulations, a direct connection exists between the analyzed computation-control parameters. It should be remembered, therefore, that a change in one may, and likely will, necessitate a modification of one or more others. At least, close scrutiny of other computation-control parameters must be made if a change in a given value is desired or required.

#### Boundary-Condition Errors

Sometimes boundary-value data are erroneous because of improper leveling of the gage recorder or malfunctioning of the recorder itself. Commonly, the magnitude of such errors may not be significant enough to inhibit or terminate a flow simulation. However, the flow results produced with erroneous boundary-value data may be of questionable validity. Therefore, thorough preprocessing of model boundary-value data is vitally important and highly recommended.

Sensitivity tests were made to illustrate the effects of using erroneous boundary-value data in the tidal Potomac River flow model. The results of one such test are illustrated in figure 8. In this figure, water-surface elevations measured and computed near Key Bridge are plotted with +10-cm and −10-cm datum adjustments to the boundary-value data at Indian Head. As can be seen from figure 8, the computed hydrograph is shifted vertically upward and downward, respectively, for the simulation made with a +10-cm and −10-cm datum adjustment. Consequently, precise leveling of gage recorders is required. Furthermore, the need to establish a common vertical datum for all gages throughout the network is critical.

Another important consideration in the recording of boundary-value data, as well as model calibration and verification data, is the need for accurate synchronized timing of measurements. Although not illustrated herein, use of improperly timed data may yield model-computed hydrographs that are shifted in phase compared to those actually measured. Thus, model calibration and verification may be unnecessarily and unduly complicated and may, in fact, result in an inaccurate or invalid "calibrated" model.

#### Initial-Condition Errors

Initial-value data may be obtained from measurements, computed from steady-state approximations, computed from previous simulations, or simply estimated. Com-

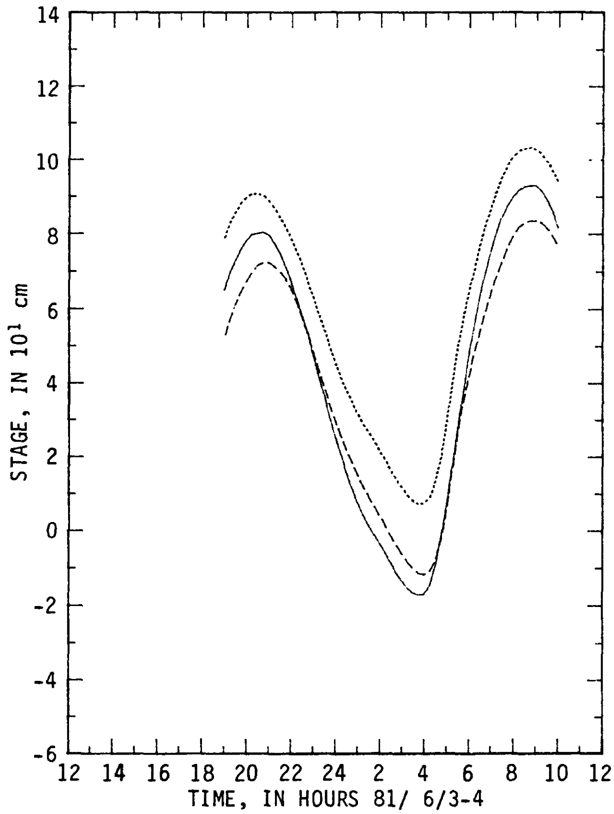


**Figure 8.** Measured (solid line) water-surface elevations near Key Bridge versus computed by use of +10-cm (dotted line) and −10-cm (dashed line) datum adjustments at Indian Head.

puted flow results obtained from simulations in which initial-value data are estimated or otherwise approximated must be carefully scrutinized. The consequences of erroneous initial-value data may affect the simulation for some period of time.

The results of simulations made with estimated and hypothesized initial conditions are shown in figures 9 and 10. Discharges computed for the Potomac River at Indian Head are shown in figure 9, whereas water-surface elevations computed near Key Bridge during the same simulations are plotted in figure 10. Estimated initial conditions were determined by assuming that quiescent water conditions exist and that a level water surface prevails throughout the channels of the network. Hypothesized initial conditions were determined by prorating discharges and water-surface elevations throughout the tidal river by using known boundary conditions in conjunction with estimated flow conditions. (Initial discharge conditions were adjusted on the basis of using known freshwater inflow at Chain Bridge and an approximation of the flood-cycle discharge at Indian Head. Initial water-surface elevation conditions were adjusted by using the known water-surface elevation at Indian Head and assuming an elevation increase to Chain Bridge. Null discharges and constant water-surface elevations were assumed throughout the tributaries and embayments.) The

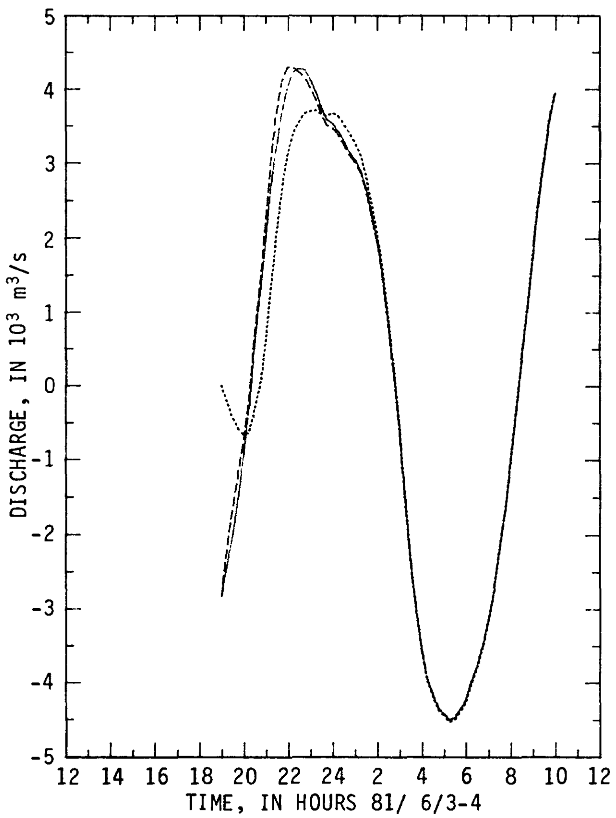


**Figure 9.** Discharges computed for the Potomac River at Indian Head by use of known (solid line), estimated (dotted line), and hypothesized (dashed line) initial conditions.

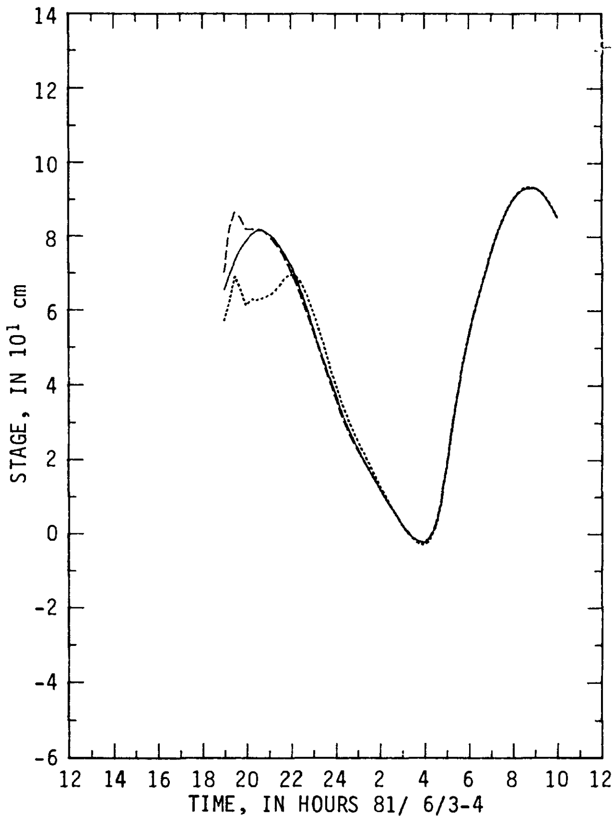


**Figure 10.** Water-surface elevations computed for the Potomac River near Key Bridge by use of known (solid line), estimated (dotted line), and hypothesized (dashed line) initial conditions.

results of simulations that used these approximated initial conditions indicate convergence of the model to the true results that were computed with known initial conditions within approximately 7 hours simulated time (see figs. 9 and 10). At approximately 0200 hours on June 4, convergence of the simulations is achieved. Thus, flow simulations of the tidal Potomac River model can be made with estimated or otherwise approximated initial-value data. However, a sufficient amount of "warm-up" time must be provided to permit the effects of errors in such conditions to disappear from the simulation.

### Operational Guidelines

The sensitivity analyses described above have identified the potential effects of alternative computation-control parameter settings, boundary condition errors, and initial condition errors. The result of this exercise is a set of guidelines governing operational use of the tidal Potomac River flow model. However, it must be emphasized that these model analyses have been made based on the network schematization shown in figure 3, which is depicted by the cross-sectional geometry previously described and governed by the identified set of boundary conditions. Modification of the channel and (or) cross-sectional geometry, or alteration of the boundary conditions, certainly would necessitate additional analyses and possibly result in revision of the following guidelines:

1. Determine and verify an appropriate spatial derivative weighting factor θ, likely between 0.75 and 1.0, to compute flows more frequently than every 15 minutes.
2. Establish and verify appropriate computation-control parameter settings paying particular attention to the selection of computation convergence criteria, to compute flows less frequently than every 15 minutes.
3. Use 3.5 $m^3/s$ for the discharge convergence criterion unless flow results of insufficient accuracy are achieved or subsequent analyses indicate a more appropriate value.
4. If other than null discharge conditions are known to exist at the external boundary condition locations of the tributaries and embayments, supply the known boundary conditions to the model.
5. Verify that water-surface elevations used to fulfill boundary condition requirements or to compare with measured values are referenced to the common datum (NGVD of 1929) used in the model.
6. If other than known initial conditions are used to actuate a flow simulation, allow about 8 hours simulation time for model "warm-up."

## Effects of Wind

Flow in the Potomac Estuary often is significantly influenced by changing meteorological conditions. The movement of weather fronts and their associated winds can have a pronounced impact on flow conditions in the tidal river as well. Such flow-controlling factors are important to consider in that they help define the tidal river's flushing properties. Knowledge of the capacity of the river to transport and subsequently dispose of pollutants is vital to assessing the current and future water quality conditions of the river, as well as its effects upon the estuary. Therefore, the effects of wind conditions must be considered and accounted for by the flow model.

For purposes of evaluating the significance and contribution of variable weather conditions on the flow, a meteorological recording station was established near Indian Head (station number 01–6554.80 in fig. 2). Maximum and average wind speed and direction at both 5-m and 10-m elevations above the water surface, as well as air temperature, air pressure, and solar radiation, are sensed and recorded every 30 minutes. Wind speed and direction data collected at this location are input to the flow model to account for wind influences. As mentioned in the "Channel geometry" section, the orientations of all channel segments within the network were determined from hydrographic charts. These orientations also are input to the model to permit resolution of the longitudinal component of wind stress.

Two sets of data containing significant wind influence are plotted in figures 11 and 12. Water-surface elevations recorded at Indian Head and near Key Bridge during the week of September 21–27, 1981, are shown in figure 11. Water-surface elevations recorded at Indian Head and near Wilson Bridge during the week of November 18–24, 1981, are shown in figure 12. Vectors representing the wind conditions during these time periods are plotted above the water-surface elevation hydrographs.

During the week of September 21–27, significant winds occurred on the 23d and 24th. The effects of these winds are shown as a significant depression of the recorded water-surface elevations. Although normal differences between successive high tides at these locations during this week are on the order of 10 cm, the successive highs on the 23d show a difference of approximately 70 to 80 cm. A depression of the second high on the 24th also is evident in the plots, although its significance is not as great as noted on the 23rd. A residual effect from this wind can also be seen in the data for the 25th to 27th. It is manifested as an increase in the mean elevation of the tides for these days as the wind influence diminishes.

Primarily, north and northwest winds prevailed on September 23 and 24. Wind speeds generally ranged between 10 and 30 km/h, with occasional gusts to 40 and 50 km/h. What is most significant and noteworthy regarding

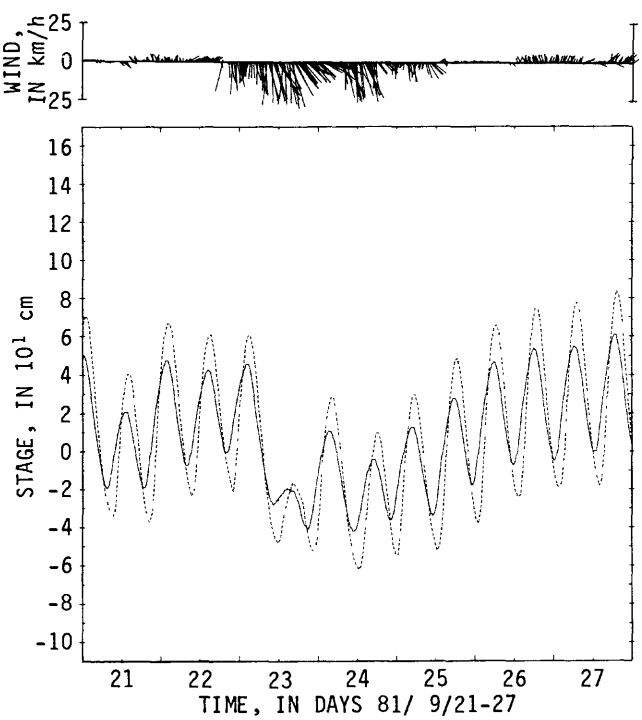


**Figure 11.** Water-surface elevations recorded at Indian Head (solid line) and near Key Bridge (dashed line) and wind data recorded at Indian Head for Sept. 21–27, 1981.

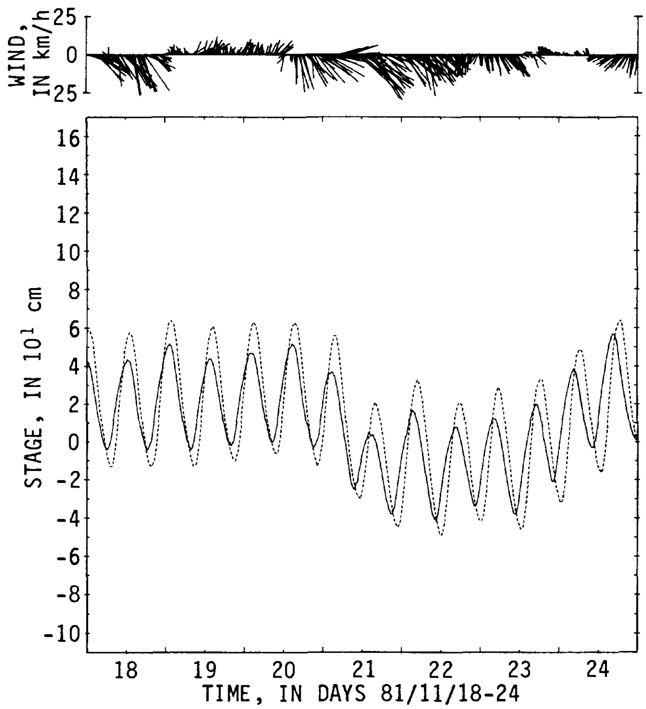


**Figure 12.** Water-surface elevations recorded at Indian Head (solid line) and near Wilson Bridge (dashed line) and wind data recorded at Indian Head for Nov. 18–24, 1981.

these wind conditions is the consistent nature of their direction. These directions, in general, coincide with the orientations of the main tidal Potomac River channel. Thus, longitudinal wind-stress components from these north and northwest winds are at or near their maximum potential values.

Wind conditions, somewhat less in speed and more variable in direction than on September 23 and 24, are evident on November 21 and 22 for the data plotted in figure 12. Although similar depressions of the tides can be seen on these two successive days and lingering residual influences from the winds also are evident, the effects of these conditions are considerably less than for the conditions illustrated by the data of figure 11. For November 21 and 22, wind directions changed from northwest to west twice before finally obtaining a somewhat more consistent north direction on the later part of the 22d. The magnitude of the wind speeds for these days is only slightly less than the conditions for September 23 and 24. As can be seen from these sets of data, the significance of the contribution of winds on the tidal river flow is highly variable and dependent on both the consistency and duration of the wind speed as well as direction.

Two simulations of the tidal Potomac River flow model, the results of which are illustrated in figures 13 and 14, amply demonstrate the model's ability to account for the influence of wind conditions. These simulations were each made with a day of record from the weeks of September 21–27, 1981, and November 18–24, 1981, as illustrated in figures 11 and 12.

In figure 13, model-computed water-surface elevations are shown plotted against those recorded near Key Bridge for September 23, 1981. At this location, the main Potomac River channel is oriented in an easterly direction. However, immediately downstream of this site, the channel turns to the south. On September 23, predominantly north and northwest winds prevailed. In the morning hours, north wind conditions occurred. Shortly after noon their direction changed to northwest. Due to the primarily south to southeast alignment of the main Potomac River channel, north and northwest winds have the most dramatic effect on river flow. As can be seen from figure 13, computed and measured water-surface elevations are in fairly close agreement. The computed hydrograph does, however, indicate generally higher water-surface elevations than those measured throughout most of the day. This difference, on the order of 4 to 6 cm, may be attributed to a number of factors. Although analysis of the wind conditions measured at Indian Head and at subsequent locations in the estuary downstream of Indian Head shows the behavior of the winds during these

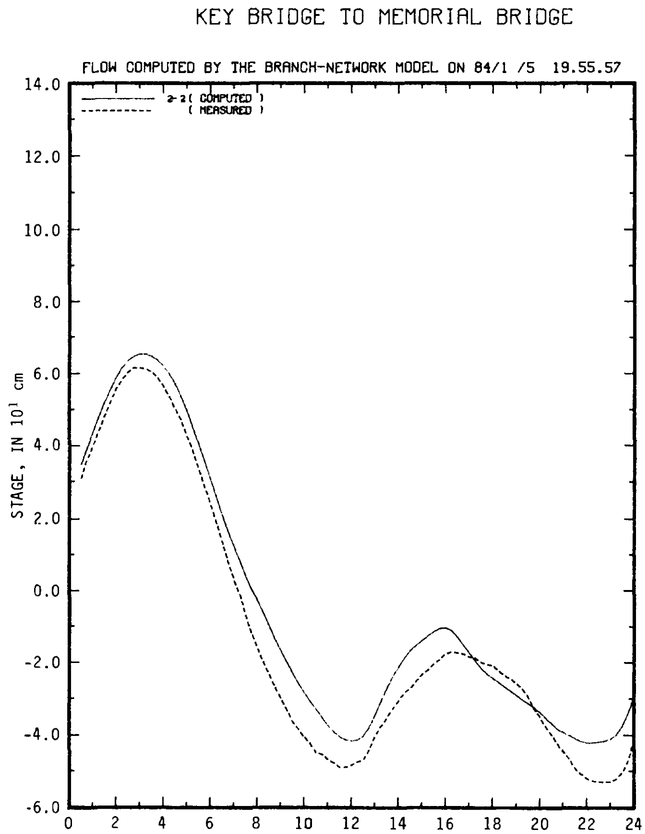


**Figure 13.** Model-generated plot of computed (solid line) versus measured (dashed line) water-surface elevations for the Potomac River near Key Bridge on Sept. 23, 1981.

times to be common throughout the area, no set of wind data was available upstream of Indian Head to substantiate this assumption. Another factor of significance in the area upstream of Wilson Bridge is the potential for sheltering of the channels from the effects of winds. The model does not account for such sheltering, and this may be a significant consideration, particularly in the channels in and around the metropolitan area. A third possible explanation for the differences in elevations noted may simply be uncertainty in the datum of the measured water-surface elevations—as a vertical shift in the measured hydrograph would serve to improve the comparison.

Model-computed water-surface elevations are shown plotted in figure 14 against those recorded near Wilson Bridge for November 21, 1981. At this location, the channel is aligned in a southerly direction. Wind conditions on November 21 varied in both magnitude and direction. In the early morning hours, northwest winds prevailed. Winds later became westerly and again returned to northwest conditions at 1000 hours. Finally, in the evening hours, winds again became westerly. As can be seen in figure 12, wind effects on the river flow for November 18–24, 1981, were not as pronounced as those of the September period. This is

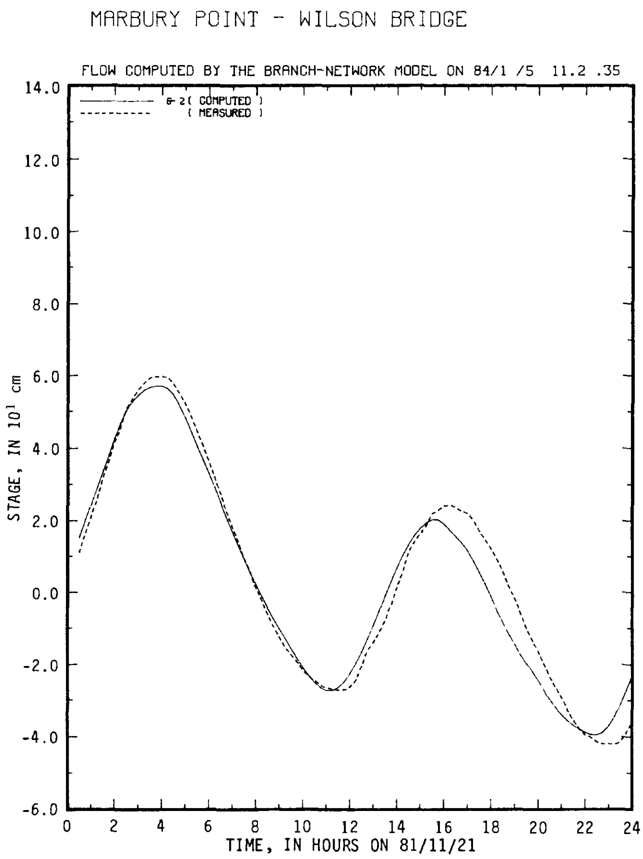


**Figure 14.** Model-generated plot of computed (solid line) versus measured (dashed line) water-surface elevations for the Potomac River near Wilson Bridge on Nov. 21, 1981.

attributable to both the direction and variability of the wind conditions. Model-computed water-surface elevations, as seen plotted in figure 14, agree more favorably with those measured than for September 23, the major differences occurring on the latter third of the day. Here again, the exact nature of the discrepancies may be attributable to one or more factors including areal behavior of the winds and sheltering of the channels. Nonetheless, these simulations give clear evidence of the model's capability to account for the effects of wind. The wind and water-surface elevation data illustrated in figures 11 and 12 clearly illustrate that the significance of such effects cannot be ignored.

## MODEL APPLICATIONS

The tidal Potomac River model can compute flow at numerous locations throughout the channel system. Basic computed flow information—that is, water-surface elevation and flow discharge—can be obtained from the model at any of the 66 cross-section locations used to describe the channel geometry of the network. To facilitate use of the model, cross-sectional locations for the main Potomac River channel have been compiled and are identified in table 3. This table, in conjunction with figure 3, can be used to identify basic computed flow information and to indicate locations at which special-purpose supplemental information may be obtained. A complete list and description of the output options available in the branch-network flow model are available as presented by Schaffranek and others (1981). Model input requirements and available output options are identified in Appendix 1.

In addition to the availability of basic computed flow information, there are special output options to aid the analytical interpretation of model results. The presentation of model results in such formats can be useful in situations where analyses of the flow dynamics of a system, such as the tidal Potomac River, are being made to evaluate a river's mixing and (or) flushing capabilities. Frequently, knowledge of such physical properties can be useful for predicting water-treatment requirements and for evaluating the quantities of municipal and industrial waste water that can be tolerated by the system. In the branch-network flow model, output options have been specifically designed to facilitate analysis of the flow dynamics in order to both evaluate and illustrate the capacity of a channel system to dispose of contaminants. Two particular output formats, particle transport plots and flow-volume summaries, available in the tidal Potomac River flow model can prove useful for assessing the quantity, and subsequently the quality, of water available throughout the system. Flow information provided in such formats can be valuable in the appraisal, comparison, and comprehension of the significance of various water management plans.

**Table 3.** Potomac River cross-section locations for the branch-network flow model

| Branch number | Junction number | Cross section number | Location | Station number | River mile location | Downstream distance in feet |
|---|---|---|---|---|---|---|
| 1 | 1 | 1 | Chain Bridge | 01–6465.80 | 116.8 | 0 |
| | | 2 | | | 115.4 | 7642 |
| | | 3 | | | 114.3 | 13527 |
| | 2 | [1]4 | | | 113.3 | 18366 |
| 2 | 2 | 1 | Key Bridge | | 113.3 | 18366 |
| | | 2 | Wisconsin Ave. | 01–6476.00 | 112.8 | 21349 |
| | 3 | [1]3 | | | 112.0 | 25620 |
| 3 | 3 | 1 | Memorial Bridge | | 112.0 | 25620 |
| | 4 | [1]2 | | | 111.0 | 31049 |
| 4 | 4 | 1 | 14th St. Bridge | | 111.0 | 31049 |
| | | 2 | | | 109.7 | 37650 |
| | 5 | 3 | | | 108.6 | 43476 |
| 5 | 5 | 1 | Hains Point | | 108.6 | 43476 |
| | | 2 | | | 107.1 | 51537 |
| | 6 | [1]3 | | | 106.2 | 55737 |
| 6 | 6 | 1 | Marbury Point | | 106.2 | 55737 |
| | 7 | [1]2 | | | 104.7 | 64042 |
| 7 | 7 | 1 | Wilson Bridge | 01–6525.88 | 104.7 | 64042 |
| | | 2 | | | 104.0 | 67742 |
| | | 3 | | | 102.3 | 71111 |
| | 15 | [1]4 | | | 101.7 | 79814 |
| 8 | 15 | 1 | Broad Creek | | 101.7 | 79814 |
| | | 2 | | | 100.9 | 83984 |
| | | 3 | | | 99.7 | 90224 |
| | 16 | [1]4 | | | 98.6 | 96408 |
| 9 | 16 | 1 | Piscataway Creek | | 98.6 | 96408 |
| | | 2 | | | 97.1 | 104133 |
| | | 3 | | | 96.7 | 106457 |
| | 17 | 4 | | | 94.7 | 116757 |
| 10 | 17 | 1 | Dogue Creek | | 94.7 | 116757 |
| | 18 | 2 | | | 92.4 | 129032 |
| 11 | 18 | 1 | Gunston Cove | | 92.4 | 129032 |
| | | 2 | | | 90.5 | 138651 |
| | | 3 | | | 87.6 | 154477 |
| | 19 | 4 | Indian Head | 01–6554.80 | 86.0 | 162796 |

[1]This cross section is duplicated at this junction.

## Particle Transport

The branch-network flow model can be used to evaluate the transport and, subsequently, the disposal of pollutants or natural substances. The variable flushing capacity of the system as a function of freshwater inflow, tidal influences, and meteorological forces can be easily illustrated by using a readily available feature of the model. With the model, the movement of dissolved conservative-type substances or particulate matter can be tracked as these are transported throughout the channel system. This study of the movement of such constituents considers transport by advective processes alone; that is, movement with the velocity of the water only. From such information, the net advection of constituents over a whole number of tidal cycles can be quantified, and questions pertaining to the travel time between specific locations within the system can be answered.

Data from the 30-day period beginning August 15 and ending September 13, 1981, were used to illustrate this feature of the tidal Potomac River flow model. These data are of particular interest due to the extremely low freshwater inflow conditions that prevailed. Inflow is less than the 5-year (1979–1983) average and less than 100 $m^3/s$, except for very near the end of the period. Ebb and flood discharges at Indian Head, as computed by the flow model, ranged from approximately 4,400 $m^3/s$ to 4,700 $m^3/s$. As a consequence of the significantly greater flow rates at Indian Head, inflow at Chain Bridge had negligible effect upon transport through the channel system during this period.

Transport of conservative-type substances and (or) particulate matter can be readily illustrated by a flow simulation using the particle-tracking feature of the model. Figure 15 presents the results of a simulation made with data from the time period August 15 through September 13, 1981. In this simulation, nine index particles representing conservative constituents or particulate matter were tracked through the main channel of the tidal river. The paths of travel of these particles, labeled A through I, are shown in figure 15. The plot represents a consecutive period of the total 30 days. The vertical axis of the time-of-travel graph in figure 15 represents the main tidal Potomac River channel between Chain Bridge and Indian Head, Md. The locations of Memorial Bridge and Wilson Bridge in Washington, D.C., and Mount Vernon and Hallowing Point in Virginia are also identified in the time-of-travel graph. The upper hydrograph in figure 15 is the inflow discharge recorded near Chain Bridge for the time period being simulated. The lower hydrograph is the water-surface elevation simultaneously recorded at Indian Head. Together these hydrographs constitute the instantaneous boundary conditions used in the flow simulation. The resultant paths of travel of the injected index particles along the main tidal Potomac River channel in response to these boundary conditions are plotted in the central part of the graph.

Much insight about the transport properties of the tidal Potomac River as a function of freshwater inflows, tidal influences, and meteorological forces can be derived through close scrutiny of the model results depicted in figure 15. During hours 30 to 180, the mean elevation of the semidiurnal tides at Indian Head gradually increases. This increase, which is on the order of 60 cm, results in a storage of water in the system. The resultant influx of water from this downstream end exceeds the magnitude of the freshwater inflow and, therefore, produces an upstream displacement of the index particles. This upstream displacement is prevalent as far upstream as Mt. Vernon. For this time period, there is also little or no net displacement of particles in the Wilson Bridge to Mt. Vernon segment. During hours 180 to 360, likewise only very minimal net displacement of index particles occurs downstream of Mt. Vernon. Those in the Wilson Bridge to Mt. Vernon segment exhibit a slight net downstream displacement. However, during the middle of the period, from hours 270 to 300, there is a shorter span of upstream movement of nearly all particles in response to a slight increase in the mean elevation of the tides recorded at Indian Head. The general trend during hours 360 to 540 is a net downstream displacement of all index particles. Index particle I, injected 7.2 km upstream of Indian Head at Hallowing Point, has arrived at the Indian Head location at approximately 520 hours, requiring 21 3/4 days in transit. As can be seen from the boundary-condition hydrographs for hours 360 to 540, there is a gradual but very slight increase in the mean elevation of the tides at Indian Head and a gradual increase in the inflow at Chain Bridge. It does appear, however, that particle movements—net downstream displacement—are somewhat influenced by the freshwater inflows. During hours 540 to 720 several hydraulic factors that significantly impact particle movements become evident. First and foremost, there is a threefold increase in the freshwater inflow at Chain Bridge. Secondly, there is a gradual decline in the mean elevation of the tides recorded at Indian Head. Thirdly, a significant wind occurs during the middle of the period between 600 and 630 hours. All of these factors combine to effect a more pronounced net downstream displacement of the index particles. In fact, during this time period, three more particles have reached the Indian Head location and all others are near or below the Hallowing Point location. Another interesting aspect of this simulation is a tendency throughout the entire period for the index particles to move closer to one another. This condition is caused by the combined effects of the freshwater inflow and the influx of water into the system from downstream.

The output illustrated in figure 15 demonstrates the model's ability to provide computed flow results in formats that facilitate the analysis of the transport and flushing properties of channel systems such as the tidal Potomac River. The comprehensive and voluminous output possible from such a model is readily reduced to a graphical form that permits the visual inspection and subsequent interpretation required to understand the complex hydrodynamic behavior of such riverine systems.

## Flow-Volume Assessment

Very often it is necessary, as in the computation of nutrient loads and suspended sediment concentrations, to evaluate the volume interchange throughout a waterbody as a function of changing flow conditions. Another special-purpose output available in the tidal Potomac River flow model can provide insight into the tidal cycle variability in the concentration and dispersion of nutrients and sediments. The output provided from this model option can be used to locate and identify major sources or sinks for nutrients and sediments.

The model not only computes the basic flow information required, but also calculates and tabulates flow volumes in a convenient and easily comprehensible format. Table 4 is a sample table produced by the model of accumulated flow volumes for the Potomac River at Wilson Bridge from August 15 through September 13, 1981. Flood (negative) and ebb (positive) volumes of flow in thousands of cubic meters are tabulated in table 4. These flood and ebb volumes of flow are separated by the time (enclosed in parentheses), approximated to the nearest computational time step, of slack water preceding the flow reversal. Flow volumes are tabulated on a daily basis; thus, the first volume shown for any given day is the volume of water accumulated from the beginning of the day to the first reversal. Similarly, the last

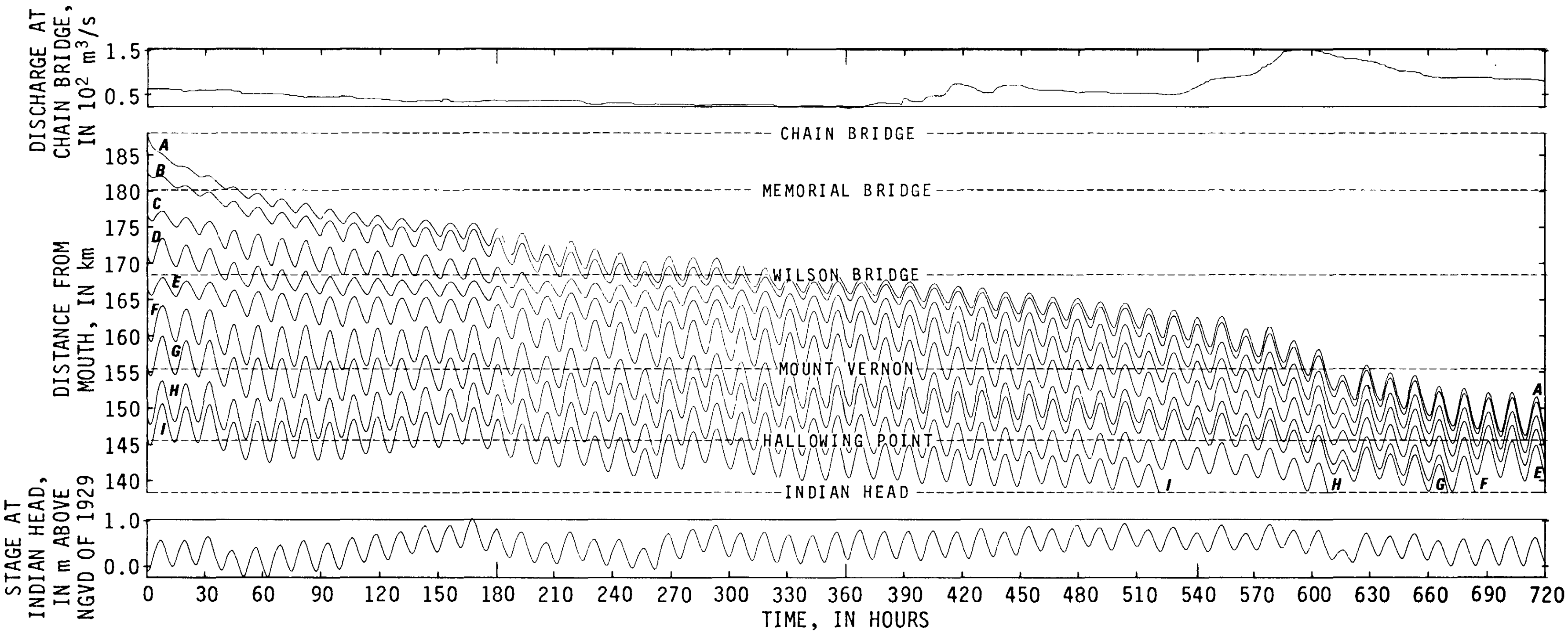


**Figure 15.** Time-of-travel plot of injected particles in the Potomac River from Aug. 15, 1981, through Sept. 13, 1981.

**Table 4.** Accumulated flow volumes, in cubic decameters, for the Potomac River at Wilson Bridge from August 15, 1981, through September 13, 1981

| Date | Flow volume | Time | Flow volume | Time | Flow volume | Time | Flow volume | Time | Flow volume |
|---|---|---|---|---|---|---|---|---|---|
| 8/15 | 3869 | (0215) | − 14782 | (0745) | 16442 | (1500) | − 13056 | (2015) | 10121 |
| 16 | 5502 | (0300) | − 14166 | (0815) | 19511 | (1630) | − 10795 | (2100) | 7540 |
| 17 | 8494 | (0415) | − 14325 | (0930) | 17286 | (1645) | − 15438 | (2200) | 4394 |
| 18 | 11739 | (0445) | − 15477 | (1015) | 18093 | (1730) | − 14645 | (2230) | 2720 |
| 19 | 13605 | (0515) | − 15435 | (1045) | 15285 | (1730) | − 14457 | (2245) | 1610 |
| 20 | 14302 | (0545) | − 14228 | (1115) | 13864 | (1800) | − 13988 | (2330) | 129 |
| 21 | 15564 | (0700) | − 13476 | (1215) | 13992 | (1900) | − 14547 | | |
| 22 | − 151 | (0030) | 18257 | (0815) | − 12058 | (1300) | 16709 | (2030) | − 10726 |
| 23 | − 2617 | (0145) | 17716 | (0930) | − 11004 | (1430) | 13702 | (2100) | − 8834 |
| 24 | − 6737 | (0300) | 16806 | (1030) | − 11893 | (1530) | 15677 | (2245) | − 2455 |
| 25 | − 10972 | (0415) | 16402 | (1145) | − 11182 | (1645) | 13447 | (2315) | − 1350 |
| 26 | − 15844 | (0500) | 15330 | (1145) | − 14966 | (1730) | 14196 | | |
| 27 | 7 | (0015) | − 13895 | (0530) | 17635 | (1315) | − 13048 | (1815) | 14883 |
| 28 | 1459 | (0115) | − 14726 | (0645) | 17517 | (1415) | − 14902 | (1930) | 12801 |
| 29 | 4121 | (0230) | − 14861 | (0800) | 15993 | (1445) | − 15607 | (2015) | 11100 |
| 30 | 5109 | (0300) | − 15208 | (0815) | 16942 | (1545) | − 14706 | (2045) | 8995 |
| 31 | 7467 | (0345) | − 14453 | (0900) | 17234 | (1615) | − 14902 | (2130) | 6237 |
| 9/01 | 10279 | (0445) | − 12920 | (0945) | 17270 | (1645) | − 14706 | (2215) | 3583 |
| 02 | 13830 | (0530) | − 12827 | (1015) | 15645 | (1715) | − 13768 | (2230) | 2055 |
| 03 | 13547 | (0600) | − 11402 | (1045) | 15028 | (1800) | − 12911 | (2330) | 190 |
| 04 | 14033 | (0645) | − 10341 | (1130) | 14700 | (1830) | − 12643 | | |
| 05 | − 3 | (0015) | 14383 | (0730) | − 9462 | (1215) | 14375 | (1930) | − 11722 |
| 06 | − 419 | (0045) | 14320 | (0815) | − 8970 | (1245) | 13408 | (2000) | − 10509 |
| 07 | − 1320 | (0130) | 16016 | (0915) | − 8170 | (1400) | 12775 | (2100) | − 7888 |
| 08 | − 3221 | (0200) | 16806 | (1000) | − 7708 | (1430) | 17323 | (2245) | − 2927 |
| 09 | − 6681 | (0330) | 19506 | (1215) | − 4863 | (1600) | 11625 | (2245) | − 1783 |
| 10 | − 9939 | (0430) | 16284 | (1200) | − 9392 | (1645) | 15706 | | |
| 11 | 3 | (0015) | − 11353 | (0515) | 17163 | (1300) | − 10002 | (1730) | 15625 |
| 12 | 1019 | (0115) | − 12524 | (0615) | 17129 | (1345) | − 12449 | (1845) | 14075 |
| 13 | 2679 | (0200) | − 13808 | (0700) | 18330 | (1430) | − 13646 | (1930) | 12963 |

volume for any given day is the volume of water accumulated from the last reversal to the end of that day.

In table 4, net negative flow volumes for successive flood and ebb tidal cycles can be seen, as for example, on August 20 (slack water time 1115 hours) and 26 (slack water time 1730 hours). These periods of negative flow volumes correspond with the time intervals of upstream displacement of index particles illustrated in figure 15 (hours 120 to 150 and 270 to 300). Likewise, the period of strong downstream displacement of injected particles (hours 600 to 630) in figure 15 is evidenced by the periods of large net positive flow volumes that occurred on September 8–9, 1981. Information as shown in table 4 can be used to quantify the tidal cycle variability of constituents being transported in the flow and to assess the significance of various factors contributing to the flow itself.

Flow-volume summaries, as compiled and tabulated in table 4, can be produced by the model at any of the cross-section locations identified in table 3. From such information, the flux of mass through any control section delineated by the cross sections can be evaluated. With this capability, evaluation of the volume interchange and, subsequently, the flushing capacity of the entire system is then possible.

## SUMMARY AND CONCLUSIONS

A one-dimensional model for simulating unsteady flow in a network of open channels has been implemented for use on the tidal Potomac River. The model is applicable to the 50-km portion of the Potomac River between Indian Head, Md., and head-of-tide immediately upstream of Chain Bridge in the District of Columbia. Included in the model application are the Anacostia River, Roosevelt Island Channel, Washington Channel, and the Tidal Basin, as well as the Broad Creek, Piscataway Creek, Dogue Creek, Gunston Cove, Pohick Bay, and Accotink Bay tidal inlets. Boundary conditions for the model consist of discharges derived from a rated gaging station upstream of Chain Bridge, water-surface elevations recorded at Indian Head, and assumed null-discharge conditions at all other extremities of the network. Water-surface elevations and flow discharges can be computed at any location throughout the system of channels.

The accuracy of the model is demonstrated by comparing computed and measured discharges throughout complete tidal cycles. In addition, comparison of computed and measured flood and ebb tidal-cycle volumes indicates model accuracy of ±10 percent. Sensitivity analyses were conducted to identify significant computation-control parameters, as well as the effects of erroneous boundary and initial conditions. The sensitivity analyses also were used to formulate a set of guidelines governing use of the model on the tidal Potomac River system.

The model demonstrates that flow in the tidal river is controlled by a number of factors. Tidal currents, freshwater inflows, and meteorological conditions are among the more important forcing functions that dictate the flow. These flow-controlling factors interact to influence tidal excursions and, thereby, define the flushing properties of the system. Tidal excursion and the variable flushing capacity of the tidal river can be examined and illustrated by the particle-tracking feature of the one-dimensional flow model. Knowledge of the flow behavior gained through this model should be useful in appraising the transport, abundance, and distribution of dissolved constituents or suspended sediments throughout the tidal Potomac River.

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## Conversion Factors

For use of readers who prefer to use inch-pound units, conversion factors for terms used in this report are listed below:

| Multiply SI units | By | To obtain inch-pound equivalent |
|---|---|---|
| | Length | |
| millimeter (mm) | 0.039 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | .621 | mile (mi) |
| | Area | |
| square meter ($m^2$) | 10.76 | square foot ($ft^2$) |
| square kilometer ($km^2$) | .386 | square mile ($mi^2$) |
| | Volume | |
| cubic meter ($m^3$) | 264.2 | gallon (gal) |
| cubic meter ($m^3$) | 35.31 | cubic foot ($ft^3$) |
| | Rate | |
| meter per second (m/s) | 3.281 | foot per second (ft/s) |
| cubic meter per second ($m^3/s$) | 35.31 | cubic foot per second ($ft^3/s$) |
| kilometer per hour (km/h) | .621 | mile per hour (mi/h) |
| cubic meter per day ($m^3/d$) | 264.2 | gallon per day (gal/d) |

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, called NGVD of 1929, is referred to as sea level in this report.

# APPENDIXES I–IV

The tidal Potomac River flow model is available for use on the U.S. Geological Survey Amdahl computer system. The program-control record format for the model is described in Appendix I. The cataloged procedure called BRANCH, as described by Schaffranek and others (1981), can be used to simplify the job-control requirements for executing the model. The BRANCH cataloged procedure, which is available through the private procedure library VG48AEP.PROCLIB, is described in Appendix II. A sample execution of the model using this cataloged procedure is given in Appendix III. Diagnostic messages produced by the model, including possible reasons for the error conditions, are identified in Appendix IV. Additional documentation for executing the general branch-network flow model is available in Schaffranek and others (1981).

## APPENDIX I, PROGRAM-CONTROL RECORD FORMAT

There are 12 basic record types used for input to the branch-network flow model. The order of record input is illustrated in Appendix III. The functional purpose of each record is given as follows:

**Network-name record** identifies the network being simulated.

**Computation-control record** defines the network dimensions, assigns the computation time increment, specifies the iteration and convergence criteria, signifies the choice of input/output units, assigns various constants and coefficients, and selects the type of output desired.

**Comment record(s)** are printed before the computation-control-record printout and may be used to describe and identify the particular simulation run.

**Branch-identity record** identifies each branch by name and number and indicates the positive flow direction, as well as the number of cross sections to be input to define the channel segments and their geometry (one such record for each branch in the network).

**Initial-condition records** (two records for each of the cross sections in the identified branch) assign the segment lengths, water temperature, flow-resistance coefficients, wind direction, and momentum coefficient, in addition to the initial values of stage and discharge.

**Cross-sectional geometry records** constitute a set of data records (preceded by one record identifying the number of data records input) defining the particular cross-sectional geometry relationships and may optionally define flow resistance as a function of stage, discharge, and/or temperature (one set for each cross section in the identified branch).

**Particle-tracking records** define the location of the main channel of the network and the initial position of index particles for purposes of permitting the tracking of such particles throughout the simulation.

**Nodal-flow record(s)** assigns the external inflows (outflows, if negative) at each internal junction.

**List-index record** controls identification of data stored in the time-dependent data base, and thereby available as boundary-value data.

**Boundary-value data records** consist of one record identifying the boundary-value data (required at each external junction) by type, station number, external junction number, recording frequency, and beginning and ending dates and times and are optionally followed by one record (containing functional boundary-condition coefficients) or by multiple records (containing actual boundary-value data, if such data are input instream).

**Wind-condition records** provide the time varying wind conditions for the simulation.

**Measured data records** consist of an initial record identifying the measured data (used for plotting versus computed results) by type, station number, junction or branch and cross-section numbers, recording frequency, and beginning and ending dates and times and are optionally followed by records containing the measured values.

Eight record types are required; four others, that is, comment, particle-tracking, wind-condition, and measured-data records are optional. All available parameter defaults can be taken simply by having the appropriate record position(s) blank. If all parameters on a particular record have acceptable defaults, the defaults can be exercised by inserting a blank record. As is identified in the following table, both metric and inch-pound equivalent default parameter values are available.

| Variable | Position | Format | Default | Definition |
|---|---|---|---|---|
| **Network-name record (one required per execution)** | | | | |
| NETNAM ----- | 1–80 | 204A | blanks | Name of the network of open channels. |
| **Computation-control record (one required per execution)** | | | | |
| IUNIT -------- | 1–2 | A2 | EN | System of units of input data (EN: in/lbs; ME: metric). |
| NBCH -------- | 3–4 | I2 | (None) | Total number of branches in the network (0<NBCH<26). |
| NJNC --------- | 5–6 | I2 | (None) | Total number of junctions (both internal and external) in the network (1<NJNC<26). |
| NBND -------- | 7–8 | I2 | (None) | Number of external boundary conditions, and internal station locations if any, to be user defined (1<NBND<16). |
| NSTEPS[1] ------ | 9–12 | I4 | ------------ | Number of time steps to be computed. |
| OUNIT -------- | 13–14 | A2 | EN | System of units of output results (EN: in/lbs; ME: metric). |
| LUGEOM ----- | 15–16 | I2 | 5 | Logical unit number of the device containing the cross-sectional geometry data (5: instream input; 10: other). |
| NIT[2] ---------- | 17–18 | I2 | 5 | Maximum number of iterations permitted per time step (usually 3≤NIT≤5). |
| IOTOPT ------- | 19 | I1 | 0 | Output option (0: print results at every time step; 1: print results at every iteration; 2: print daily summary of results; 3: plot results at every time step; 4: print monthly flow-volume summaries; 5: print terms at every time step; 6: print terms at every iteration; 7: print debug at every time step; 8: print debug at every iteration; 9: print particle locations). |
| IPLOPT ------- | 20 | I1 | 0 | Plot option (0: do not plot; 1: plot computed discharge; 2: plot computed stage; 3: plot measured versus computed discharge; 4: plot measured versus computed stage). |
| IPLDEV[3,4] ----- | 21 | I1 | 0 | Plotter device (0: line printer; 1: Tektronix (DISSPLA Postprocessor); 2: CalComp; 3: FR80; 4: Hewlett-Packard 7475; 5: TAB 132/15-G; 6: Tektronix 4014; 7: Tektronix 4105). |
| IPRMSG ------ | 22 | I1 | 0 | Option to permit the time-dependent-data storage-and-retrieval system to print messages (0: do not print message; 1: print message). |

See footnotes at end of table.

| Variable | Position | Format | Default | Definition |
|---|---|---|---|---|
| **Computation-control record (one required per execution)—Continued** | | | | |
| IPLMSG ------- | 23 | I1 | 0 | Option to permit the plotter software to print messages (0: do not print messages; 1: print messages). |
| IEXOPT ------- | 24 | I1 | 0 | Option to extrapolate initial values for unknowns from present time step values (0: do not extrapolate; 1: extrapolate). |
| TYPETA ------ | 25 | I1 | 1 | Type of functional flow-resistance relationship (1: constant; 2: temperature; 3: depth; 4: discharge; 5: Froude number; 6: Reynolds number; 7: water-surface elevation). |
| INHR[5] -------- | 26–27 | I2 | ------------ | Hour of initial-value data. |
| INMN[5] -------- | 28–29 | I2 | ------------ | Minute of initial-value data. |
| IDTM[6] -------- | 30–33 | I4 | ------------ | Simulation time increment in minutes. |
| THETA ------- | 34–36 | F3.2 | 1.0 | Finite-difference weighting factor ($\theta$) for the spatial derivatives (usually $0.6 \leq \text{THETA} \leq 1.0$). |
| QQTOL[7] ------ | 37–41 | F5.1 | ------------ | Discharge convergence criterion. |
| ZZTOL -------- | 42–46 | F5.3 | 0.01/ 0.003048 | Stage convergence criterion in feet or meters. |
| WSPEED ------ | 47–51 | F5.2 | 0.0 | Wind speed in miles or kilometers per hour. |
| WSDRAG ----- | 52–56 | F5.4 | 0.0026 | Water-surface drag coefficient. |
| H2ODEN ------ | 57–61 | F5.4 | 1.9617/ 1.011 | Water density in slugs/$ft^3$ or g/$cm^3$. |
| CHI[8] ---------- | 62–64 | F3.2 | 1.0 | Weighting factor ($\chi$) for function values in the flow equations (usually $0.5 \leq \text{CHI} \leq 1.0$). |
| IPUNIN ------- | 65 | I1 | 0 | Option to file initial condition records at the end of the simulation (0: do not file; 1: file). |
| LUINIT ------- | 66–67 | I2 | 5 | Logical unit number of device containing branch identification and initial condition records (5: instream input; 11: other). |
| NUMCOM ----- | 68 | I1 | 0 | Number of comment records following the computation-control record. |
| WDIREC ------ | 69–73 | F5.1 | 0.0 | Wind direction measured clockwise from true north. |
| INWIND ------ | 74 | I1 | 0 | Time-varying wind input (0: no; 1: yes). |
| OTTDDB ------ | 75 | I1 | 0 | Output results to time-dependent data base (0: no; 1: yes). |
| ISMOPT ------- | 76 | I1 | 0 | Option to print warning messages for segment lengths out of range (0: print messages; 1: do not print messages). |
| **Comment records (zero to nine optional)** | | | | |
| COMENT ----- | 1–80 | 20A4 | ------------ | Comments to be printed before the computation-control-record printout. |

| Variable | Position | Format | Default | Definition |
|---|---|---|---|---|
| **Branch-identification records (one required per branch)** | | | | |
| IJF ---------- | 1–2 | I2 | (None) | Junction number identifying the source of positive flow for the branch (0<IJF≤NJNC). |
| IJT ---------- | 3–4 | I2 | (None) | Junction number identifying the outlet of positive flow for the branch (0<IJT≤NJNC). |
| NSEC[9] -------- | 5–6 | I2 | (None) | Number of cross sections input to define the geometry of the branch. |
| NAME -------- | 7–46 | 10A4 | Blanks | Name of branch. |
| PRTBCH ------ | 76 | I1 | 0 | Flag for printout of branch results (0: output; 1: no output). |
| PRTSUM ------ | 77 | I1 | 0 | Flag for printout of daily summary of branch results (0: output; 1: no output). |
| PPLTBH ------ | 78 | I1 | 0 | Flag for printer plots of branch results (0: output; 1: no output). |
| PLTBCH ------ | 79 | I1 | 0 | Flag to control digital plotting of branch results (0: output; 1: no output). |
| PRTXSG ------ | 80 | I1 | 0 | Flag to control printout of cross-sectional geometry for branch (0: output; 1: no output). |
| **Initial-condition records (two required per cross section)** | | | | |
| First initial-condition record for cross section: | | | | |
| Z[10] ---------- | 1–10 | F10.3 | (None) | Initial stage value. |
| Q ----------- | 11–20 | F10.3 | (None) | Initial discharge value. |
| DX ---------- | 31–40 | F10.2 | (None) | Segment length. |
| T ------------ | 41–50 | F10.2 | 59.0/15.0 | Water temperature, in degree Fahrenheit or Celsius. |
| RN ---------- | 51–80 | 3E10.4 | (None) | Coefficients of flow-resistance relationship, i.e., η(x) = RN(1) + RN(2)*x + RN(3)*x**2. |
| Second initial-condition record for cross section: | | | | |
| ORIENT ------- | 1–10 | F10.3 | 0.0 | Segment orientation measured clockwise from true north. |
| BETVEL ------ | 11–20 | F10.3 | 1.0 | Momentum coefficient at cross section. |
| **Cross-sectional geometry records (one set required per cross section)** | | | | |
| First record of cross-sectional geometry identifies the number of input data records: | | | | |
| IPT ---------- | 1–2 | I2 | (None) | Number of cross-sectional geometry data records (1<IPT≤20). |
| XSTATN ------ | 4–11 | I8 | ------------ | Field station number of cross-section location. |
| GDATUM ----- | 66–72 | F7.3 | ------------ | Datum correction for cross-sectional data. |
| ITYPEO ------- | 73–80 | 4A2 | ------------ | Type of data output (' Z': stage; ' Q': discharge; ' A': area; ' B': top-width). |
| IPT number of cross-sectional geometry data records: | | | | |
| ZA[11] --------- | 1–10 | F10.3 | (None) | Stage at which corresponding area and top width were measured. |
| AA ---------- | 11–20 | F10.3 | (None) | Cross-sectional area at specified stage. |
| BB ---------- | 21–30 | F10.3 | (None) | Top width at specified stage. |

See footnotes at end of table.

| Variable | Position | Format | Default | Definition |
|---|---|---|---|---|
| **Cross-sectional geometry records (one set required per cross section)—Continued** | | | | |
| ETA[12] --------- | 31–40 | E10.4 | (None) | Flow resistance at specified stage, discharge, or temperature. |
| QA[12] ---------- | 41–50 | F10.3 | (None) | Discharge for specified flow resistance. |
| TA[12] ---------- | 51–60 | F10.3 | (None) | Temperature for specified flow resistance. |
| **Particle-tracking records (only required for IPROPT equal 9)** | | | | |
| First particle-tracking record: | | | | |
| ITBCUS ------- | 1–2 | A2 | ------------ | Type of boundary-value data supplied at upstream end of main channel. |
| IBCHUS ------- | 6–7 | I2 | ------------ | Branch number of upstream boundary. |
| ISECUS ------- | 10 | I1 | ------------ | Cross-section number of upstream boundary. |
| ITBCDS ------- | 12–13 | A2 | ------------ | Type of boundary-value data supplied at downstream end of main channel. |
| IBCHDS ------- | 17–18 | I2 | ------------ | Branch number of downstream boundary. |
| ISECDS ------- | 21 | I1 | ------------ | Cross-section number of downstream boundary. |
| Second particle-tracking record: | | | | |
| XPTLOC ------ | 1–80 | 10F8.2 | ------------ | Initial particle locations (measured from upstream boundary location). |
| **Nodal-flow record(s) (one value per junction; 10 junctions per record)** | | | | |
| W[13] ----------- | 1–80 | 10F8.2 | 0.0 | External inflow (or outflow) at junction (constant nodal flow for duration of simulation assumed). |
| **List-index record for time-dependent data base (one required per execution)** | | | | |
| LISTB -------- | 38–39 | I2 | 0 | Option to list the time-dependent data base index before computation (1: print only the directory list; −1: print the directory list and the chronological summary; 0: do not print). |
| LISTA -------- | 46–47 | I2 | 0 | Option to list the time-dependent data base index after computation (1: print only the directory list; −1: print the directory list and the chronological summary; 0: do not print). |
| **Boundary-value data records (one set required per external boundary condition)** | | | | |
| First record of each boundary-value data set is a data-definition record: | | | | |
| ITYPE[14] ------- | 1–2 | A2 | ' Z' | Type of boundary-value data specified (' Z': stage; ' Q': discharge). |
| IBJNC -------- | 3–4 | I2 | (None) | Junction number of external boundary location (0<IBJNC≤NJNC). |

| Variable | Position | Format | Default | Definition |
|---|---|---|---|---|
| **Boundary-value data records (one set required per external boundary condition)—Continued** | | | | |
| NDATA ------- | 5–7 | I3 | 0 | Number of boundary-value data input (0: implies data are to be retrieved from the time-dependent data base; 1: boundary condition is specified by an equation; >1: identifies the number of boundary-value data records to be read instream). |
| DTT[15] --------- | 8–9 | F2.0 | (None) | Recording interval of boundary-value data in minutes. |
| ISTATN ------- | 10–17 | I8 | (None) | Station identification number of boundary-value data specified. |
| ITIME -------- | 25–39 | 5(I2,1X) | (None) | Beginning date and time of boundary-value data (YR/MO/DY HR:MN). |
| NTIME -------- | 45–59 | 5(I2,1X) | (None) | Ending date and time of boundary-value data (YR/MO/DY HR:MN). |
| NOPCRD ------ | 60 | A1 | 1 | Number of data input per record (in F10.3 format). |
| IDREAD[15] ----- | 62–65 | I4 | (None) | Number of boundary-value data recorded per day. |
| DATUM[16] ----- | 66–72 | F7.3 | 0.0 | Datum correction for stage boundary-value data. |
| IFVBCH[17] ----- | 78–79 | I2 | ------------ | Branch number for flow volume summary output. |
| IFVSEC[17] ------ | 80 | I1 | ------------ | Cross-section number for flow volume summary output. |
| Boundary-value data records if data are input instream ((NDATA-1)/NOPCRD+1 number): | | | | |
| ZQ ----------- | 1–80 | 8F10.3 | (None) | Stage or discharge boundary value. |
| One record containing coefficients if boundary condition is specified by an equation: | | | | |
| ZQBVCO ------ | 1–40 | 4E10.4 | 0.0 | Coefficients of the boundary-value equation, i.e., Z(Q) = ZQBVCO(1) + ZQBVCO(2)*Q + ZQBVCO(3)*Q**2 + ZQBVCO(4)*Q**3. |
| **Time-varying wind condition records (only required when INWIND equals 1; one data-definition record followed by a maximum of 372 data records)** | | | | |
| ITYPE -------- | 1–2 | A2 | ' W' | Type of time-dependent data requested (' W': wind speed and direction). |
| NWDATA ----- | 5–7 | I3 | 0 | Number of data input. |
| WDTT[15] ------- | 8–9 | F2.0 | ------------ | Data time interval in minutes. |
| ISTATN ------- | 10–17 | I8 | ------------ | Station identification number of time-dependent data specified. |
| IWTIME ------ | 25–39 | 5(I2,1X) | ------------ | Beginning date and time of data (YR/MO/DY HR:MN). |
| NWTIME ------ | 45–59 | 5(I2,1X) | ------------ | Ending date and time of data (YR/MO/DY HR:MN). |
| NWREAD[15] ---- | 62–65 | I4 | ------------ | Number of data input per day. |
| WINDSP ------ | 1–10<br>21–30<br>41–50<br>61–70 | F10.3 | ------------ | Wind speed in mph or kph. |

| Variable | Position | Format | Default | Definition |
|---|---|---|---|---|
| **Time-varying wind condition records (only required when INWIND equals 1; one data-definition record followed by a maximum of 372 data records)—Continued** | | | | |
| WINDDR ------ | 11–20<br>31–40<br>51–60<br>71–80 | F10.3 | ------------ | Wind direction measured clockwise from true north. |
| **Measured-data records (one set optionally required when plotting computed versus measured data)** | | | | |
| First record of each measured-data set is a data-definition record: | | | | |
| MYTYPE[18] ---- | 1–2 | A2 | ' Z' | Type of measured data supplied (' Z': stage; ' Q': discharge). |
| MJNC[19] ------- | 3–4 | I2 | ------------ | Junction number of measured data location (0<MJNC≤NJNC). |
| MDATA ------- | 5–7 | I3 | 0 | Number of measured data input (0: implies data are to be retrieved from the time-dependent data base; >1: identifies the number of measured-data records to be read instream). |
| CDTT[15] ------- | 8–9 | F2.0 | (None) | Input interval of measured data in minutes. |
| MSTATN ------ | 10–17 | I8 | (None) | Station identification number of measured data specified. |
| MITIME[20] ----- | 25–39 | 5(I2,1X) | (None) | Beginning date and time of measured data (YR/MO/DY HR:MN). |
| MNTIME[20] ---- | 45–59 | 5(I2,1X) | (None) | Ending date and time of measured data (YR/MO/DY HR:MN). |
| NOPCRD ------ | 60 | A1 | 1 | Number of data input per record (in F10.3 format). |
| MDREAD[15 21] -- | 62–65 | I4 | (None) | Number of measured data input per day. |
| CDATUM ----- | 66–72 | F7.3 | 0.0 | Adjustment factor for measured data. |
| MBCH[19] ------- | 78–79 | I2 | ------------ | Branch number of measured data location (0<MBCH≤NBCH). |
| MSEC[19] ------- | 80 | I1 | ------------ | Cross-section number of measured data location (0<MSEC≤NSEC). |
| MDATA number of measured-data records if data are input instream: | | | | |
| ZQMEAS ------ | 1–10 | F10.3 | (None) | Measured stage or discharge value. |

---

[1]If not specified, the number of time steps to be computed is determined from the time span specified on the *first* boundary-value data definition record.

[2]The computation is permitted to continue using the previous computed values whenever the maximum number of iterations is exceeded. A message is printed, however, identifying the maximum stage and discharge deviations and the location(s) of their occurrence.

[3]These variables are only applicable for IPLOPT ≠ 0.

[4]Tektronix, CalComp, and FR80 plots are produced in auxiliary operations from files of plotter instructions generated during the simulation. In order to produce plots on devices 4-7 the simulation must be run interactively. IPLDEV equal 6 is for a Tektronix 4014 terminal with baud rate set at 1200 bps. By incorporating the appropriate emulator subroutine calls in the DEVSET subroutine of BRANCH, other plotter device types which are supported by the local version of the DISSPLA software can be designated as IPLDEV 8 and (or) 9.

[5]If not specified, the time of initial-value data is taken as the time of the *first* boundary-value datum.

[6]If not specified, the simulation time step is set to the data recording interval on the *first* boundary-value data definition record.

[7]The default discharge convergence criterion is taken as 0.5 percent of the minimum (absolute value greater than zero) initial-value discharge. If all initial discharges are zero the default discharge convergence criterion is set to one.

[8]If not specified, the weighting factor $\chi$ is set equal to the weighting factor for the spatial derivatives, $\theta$.

[9]The total number of cross sections used to define the geometry of all branches composing the network must not exceed the maximum number of cross sections allocated (NBSEC≥ΣNSEC(I); I=1,NBCH) for the particular version of the model program being used. In general, it is recommended not to exceed the maximum number of cross sections allocated per branch, which is 4 in this model-program version.

[10]Initial values at external boundary locations default to the first boundary-value datum input.

[11]Stage-area-width relationships must be input in sequence starting with the values at the lowest stage.

[12]If flow resistance is defined as a tabular-functional relationship then a complete table of functional relationship values must be defined which agrees with the number of cross-sectional geometry data records input.

[13]Code nodal-flow values in sequence according to the junction numbering scheme.

[14]If boundary-value data sets are input from both disk and instream, input disk boundary-value data definition records first beginning wtih the boundary-value data recorded at the greatest frequency (smallest time interval).

[15]The data interval and the number of data per day need not both be specified: either is sufficient.

[16]Appropriate uses of the DATUM adjustment factor are to change datum references or to correct for known or suspected recorder elevation shifts.

[17]These variables permit the accumulation and compilation of flow volumes at internal station locations of the network. The station identification number must be provided to accommodate filing flow volumes for a particular location.

[18]Only one set of measured data can be input per branch of the network.

[19]The location of measured data may be defined either by junction number or by branch and cross-sectional numbers.

[20]All sets of measured data must begin and end at a common date and time in the same calendar day. This date and time must be within the time span of the simulation.

[21]All measured data must be supplied at the computation time step frequency.

## APPENDIX II, JOB CONTROL

There are 11 primary data files identified in the BRANCH cataloged procedure. The data-station reference and time-dependent data files (identified by the symbolic parameter prefixes GI and DA, respectively) are necessary if boundary-value data are stored on a direct-access disk by the model's time-dependent data processing support system for subsequent inclusion in the model. The cross-sectional geometry file (identified by the symbolic parameter prefix XS) contains stage-area-width tables for input to the model. The data files identified by the symbolic parameter prefixes ICI and ICO are provided for model input and output, respectively, of initial-value data. The remaining six files are intended for model output purposes. The particle-tracking file (identified by the symbolic parameter prefix PT) contains the computed paths of travel of injected index particles for subsequent plot generation. The flow-volume output file (identified by the symbolic parameter prefix FV) retains cumulative flow volumes for the purpose of printing monthly summaries. The instantaneous volume file (identified by the symbolic parameter prefix TV) retains flow volumes computed at the computation time-step frequency. The DISSPLA compressed file (identified by the symbolic parameter prefix TT) is generated if subsequent plotting of model-computed flow information is to be accomplished via the Postprocessor. The CalComp and FR80 magnetic tape plot files (identified by the symbolic parameter prefixes CC and FR, respectively) are generated if plots are to be produced using a CalComp drum or flatbed, electromechanical pen plotter or an Information International, Inc. FR80 microfilm recorder.

BRANCH Cataloged Procedure Description

| Symbolic parameter | Default | Description |
|---|---|---|
| PROG | BRANCH | Version of the branch-network-model program to be executed (25 branch and 15 boundary-condition versions = BRANCZ: complete; BRANOO: without OPLOT routine; BRNODP: without DADIO routine/15 branch and 5 boundary-condition versions = BRANCH: complete; BRANOP: without OPLOT routine; BRANOD: without OPLOT and DADIO routines.) |
| ECORE | 650K | Region size (K bytes) required to execute the program (BRANCZ: 800K; BRANOO: 510K; BRNODP: 740K; BRANCH: 650K; BRANOP: 360K; BRANOD: 250K). |
| ETIME | 1 | Execution time for the program, where time is specified in minutes. |
| GIUNIT | 3350 | Unit type of the device containing the data-station reference file for the data base of time-dependent, boundary-value data. |
| GIVOL | (None) | Volume serial number of the device containing the data-station reference file for the data base of time-dependent, boundary-value data. |
| GINAME | NULLFILE | Data set name of the data-station reference file for the data base of time-dependent, boundary-value data. |
| DAUNIT | 3350 | Unit type of the device containing the data base of time-dependent, boundary-value data. |
| DAVOL | (None) | Volume serial number of the device containing the data base of time-dependent, boundary-value data. |
| DANAME | NULLFILE | Data set name of the data base of time-dependent, boundary-value data. |
| XSUNIT | 3350 | Unit type of the device containing the cross-sectional geometry data file. |
| XSVOL | (None) | Volume serial number of the device containing the cross-sectional geometry data file. |
| XSNAME | NULLFILE | Data set name of the cross-sectional geometry data file. |

BRANCH Cataloged Procedure Description—Continued

| Symbolic parameter | Default | Description |
|---|---|---|
| ICIUNIT | 3350 | Unit type of the device containing the input initial-value data file. |
| ICIVOL | (None) | Volume serial number of the device containing the input initial-value data file. |
| ICINAME | NULLFILE | Data set name of the input initial-value data file. |
| ICOUNIT | 3350 | Unit type of the device to contain the output initial-value data file. |
| ICOVOL | (None) | Volume serial number of the device to contain the output initial-value data file. |
| ICONAME | NULLFILE | Data set name of the output initial-value data file. |
| ICODISP | NEW | The current disposition of the output initial-value data file; code OLD if it presently exists. |
| PTUNIT | 3350 | Unit type of the device to contain the particle tracking data file. |
| PTVOL | (None) | Volume serial number of the device to contain the particle tracking data file. |
| PTNAME | NULLFILE | Data set name of the particle tracking data file. |
| PTDISP | NEW | The current disposition of the particle tracking data file; code OLD if it presently exists. |
| TVUNIT | 3350 | Unit type of the device to contain the instantaneous volume output file. |
| TVVOL | (None) | Volume serial number of the device to contain the instantaneous volume output file. |
| TVNAME | NULLFILE | Data set name of the output file of instantaneous volumes. |
| TVDISP | OLD | The current disposition of the output file of instantaneous volumes; code NEW if a new file is to be created. |
| FVUNIT | 3350 | Unit type of the device to contain the cumulative flow-volume output file. |
| FVVOL | (None) | Volume serial number of the device to contain the cumulative flow-volume output file. |
| FVNAME | NULLFILE | Data set name of the cumulative flow-volume output file. |
| FVDISP | OLD | The current disposition of the cumulative flow-volume output file; code NEW if a new flow-volume file is to be created. |
| TTUNIT | 3350 | Unit type of the device to contain the DISSPLA compressed file for Postprocessor plotting. |
| TTVOL | (None) | Volume serial number of the device to contain the DISSPLA compressed file for Postprocessor plotting. |
| TTNAME | NULLFILE | Data set name of DISSPLA compressed file. |
| TTDISP | OLD | The current disposition of the DISSPLA compressed file; code NEW if a new file is to be created. |
| CCVOL | (None) | Volume serial number of the standard-labeled, magnetic tape to contain the CalComp plot file. |
| CCNAME | NULLFILE | Data set name of the CalComp plot file. |
| FRVOL | (None) | Volume serial number of the standard-labeled, magnetic tape to contain the FR80 plot file. |
| FRNAME | NULLFILE | Data set name of the FR80 plot file. |

## APPENDIX III, MODEL EXECUTION SETUP

The following is an example setup to execute the branch-network flow model of the tidal Potomac River. Cross-sectional geometry, boundary-value, and initial-value data are retrieved from the identified computer data files.

```
//COMPUTER JOB CARD
//PROCLIB DD DSN=VG48AEP.PROCLIB,DISP=SHR
//BRANCZ EXEC BRANCH,PROG=BRANCZ,ECORE=800K,ETIME=3,
// XSNAME='VG48AEP.BRANCH.POTOMAC.GEOTRKQM',
// GINAME='VG48ABT.GPHINDX1.POTOMAC',
// ICINAME='VG48AEP.BRANCH.POTOMAC.ICB10909',
// DANAME='VG48AEP.POTOMAC.TIMEDPDT.DATAFILE'
//SYSIN DD *
THE TIDAL POTOMAC RIVER : CHAIN BRIDGE TO INDIAN HEAD
EN252510    ME10  000  11       15.60125.0.015      .0015      .50 114     1
BRANCH-NETWORK FLOW MODEL APPLICATION TO THE POTOMAC RIVER BETWEEN CHAIN BRIDGE
AND INDIAN HEAD INCLUDING THE ANACOSTIA RIVER, WASHINGTON CHANNEL, ROOSEVELT
ISLAND CHANNEL, THE TIDAL BASIN, AND THE TIDAL EMBAYMENTS OF BROAD CREEK, DOGUE
CREEK, PISCATAWAY CREEK, GUNSTON COVE, ACCOTINK BAY, AND POHICK BAY.
                                                  525.0


 Z19      1655480        81/09/09 00:30       81/09/09 01:00       96  -9.84
 Q 1  1   1646500        81/09/09 00:30       81/09/09 01:00       48
5390.0
 Q 8  1

 Q13  1

 Q14  1

 Q20  1

 Q21  1

 Q22  1

 Q24  1

 Q25  1

 W    230                81/09/09 00:30       81/09/09 01:00
       4.7    114.5        4.5     125.6
/*
//
```

## APPENDIX IV, DIAGNOSTIC MESSAGES

The following diagnostic messages are generated by the MAIN program and the subroutines of the branch-network flow model. Additional comments on the possible reasons for the error are given below the message:

INITIAL STAGE VALUE UNSPECIFIED IN BRANCH (I) SECTION (J)

Initial values of stage and discharge must be supplied at all cross sections.

INITIAL STAGE XXXXX.XX OUT OF DEFINED RANGE OF CHANNEL GEOMETRY FOR BRANCH (I) SECTION (J)

The initial value of stage is out-of-range of the stage-area-width geometry table for the specified cross section.

IMPROPER NUMBER OF CROSS-SECTIONAL DATA (2<=IPT<=20)

More than one and 20 or fewer stage-area-width relationships must be input to define the geometry at each cross section.

DUPLICATE, OR OUT-OF-ORDER, STAGES IN CHANNEL-GEOMETRY TABLE FOR BRANCH (I) SECTION (J)

Unique stage-area-width relationships defining the cross-sectional geometry must be input in sequential order beginning with the lowest stage value.

MATRIX NOT SQUARE: REVIEW SCHEMATIZATION AND EXTERNAL BOUNDARY-CONDITION SPECIFICATIONS

This condition can be caused by improper schematization and (or) input parameter errors.

INVALID BOUNDARY-VALUE DATA PARAMETER(S)

Information on a boundary-value data-definition record is invalid or inconsistent.

INVALID MEASURED DATA PARAMETER(S)

Information on a measured data-definition record is invalid or inconsistent.

MATRIX IS SINGULAR

The matrix has no inverse. This condition can be caused by improper boundary conditions or by schematization errors.

TOO MANY MEASURED DATA LOCATIONS (MXMD=X)

Up to X sets of measured data can be input in this version of the model.

JUNCTION (J) OF BOUNDARY-VALUE DATA IMPROPERLY SPECIFIED (0<IBJNC<XX)

The junction number must be greater than 0 and less than XX.

IMPROPER NUMBER OF MEASURED DATA SPECIFIED (1<=MDATA<=XXX)

Up to XXX measured data can be input at each location.

INVALID BRANCH (I) SECTION (J) SPECIFIED FOR MEASURED DATA

The branch and cross-section numbers identifying a measured data location are errant or inconsistent with the network schematization.

JUNCTION (J) OF MEASURED DATA NOT FOUND

The specified junction number of a measured data location is in error.

INITIAL VALUE(S) OUT OF DEFINED RANGE OF CHANNEL GEOMETRY

One or more initial stage values are out-of-range of the respective stage-area-width geometry table.

INITIAL OR COMPUTED STAGE RESULTS IN ZERO OR NEGATIVE AREA AND (OR) TOP WIDTH

The initial or computed stage value is inconsistent with the stage-area-width geometry table.

MAXIMUM ITERATIONS EXCEEDED AT (HR:MN) ON (YR/MO/DY) Z-ZP (I,J) = XXX.XXXX Q-QP (I,J) = XXXXXX.X

Convergence conditions were not satisfied during the specified time step. The stage and discharge printed represent the maximum difference between the last successive solutions. Computation continues using the last computed values.

EXECUTION TERMINATED DUE TO INCORRECT ATTEMPT TO UPDATE CUMULATIVE FLOW-VOLUME FILE

The cumulative flow-volume file is allocated to contain flow volumes computed for a given calendar year and a specific network. An attempt to add data from a different network or calendar year produces the above error message.

STEP SIZE IN PLOT SCALE ALGORITHM EXCEEDS MAXIMUM LIMIT

The magnitude of the quantity to be plotted is prohibitively large.

INSUFFICIENT NUMBER OF BOUNDARY-VALUE DATA INPUT INSTREAM

Check the number of boundary-value data defined.

COMPUTED STAGE IS NOW OUT OF BOUNDS ON LOWER/UPPER END OF GEOMETRY TABLE, BRANCH (I) SECTION (J), AREA AND WIDTH EXTRAPOLATED

Review cross-sectional geometry table definition.

COMPUTED STAGE EXCEEDS RANGE OF GEOMETRY TABLE BY 20%, BRANCH (I) SECTION (J), EXECUTION TERMINATED

Check cross-sectional geometry table definition.

IMPROPER NUMBER OF BRANCHES SPECIFIED (1<=NBCH<=XX)

Verify number of branches input against model version.

IMPROPER NUMBER OF JUNCTIONS SPECIFIED (2<=NJNC<=XX)

Check number of junctions defined.

IMPROPER NUMBER OF EXTERNAL BOUNDARIES SPECIFIED (2<=NBND<=XX)

Check number of external boundaries defined.

TIME OF INITIAL-VALUE DATA INCORRECT

Verify time of initial-value data specified.

INVALID STATION NUMBER (XXXXXXXX) SPECIFIED FOR BRANCH (I) SECTION (J)

Correct the station number identified as incorrect.