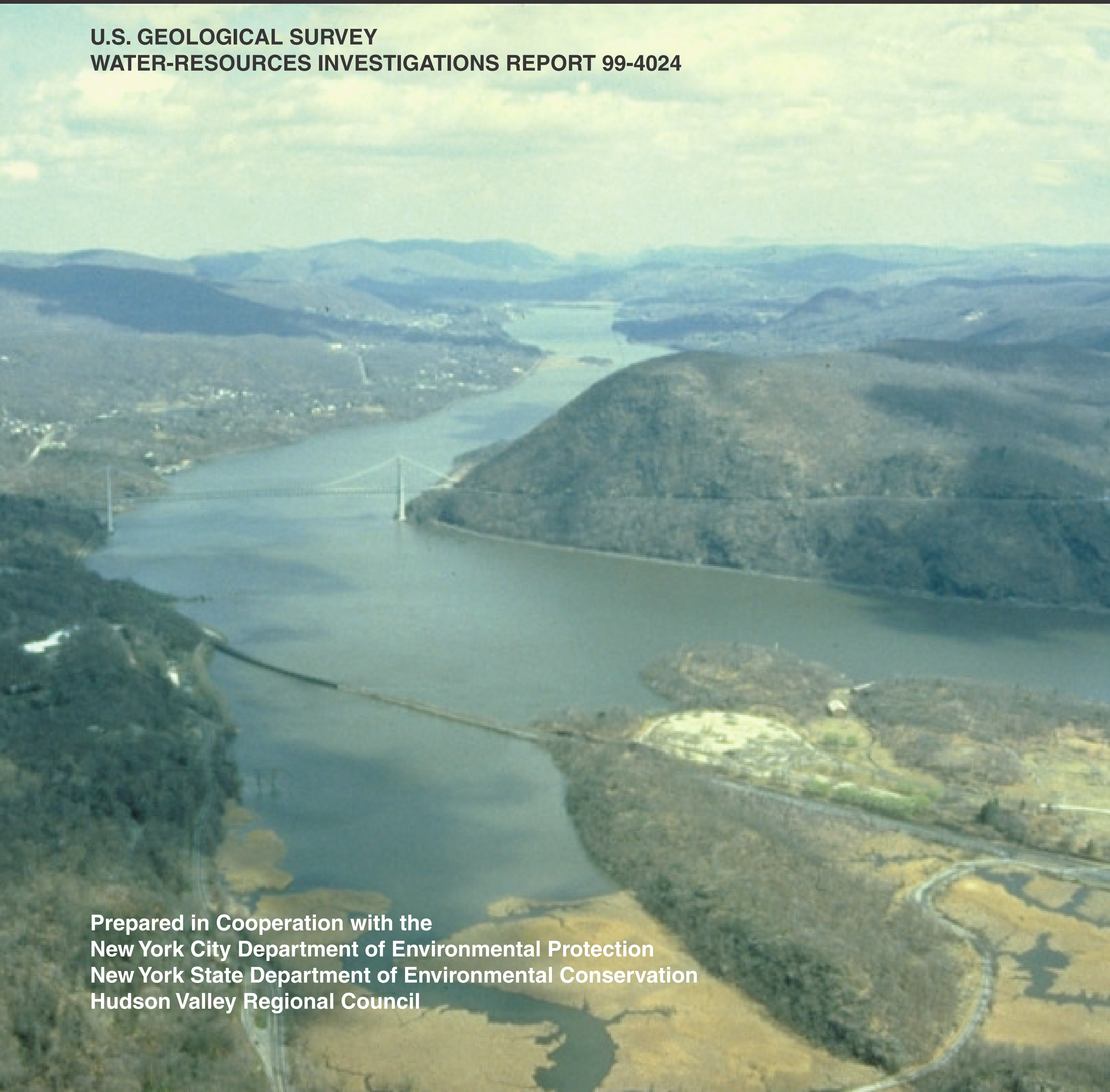
Salt-Front Movement in the Hudson River Estuary, New York—

Simulations by One-Dimensional Flow and Solute Transport Models

U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS REPORT 99-4024



Prepared in Cooperation with the
New York City Department of Environmental Protection
New York State Department of Environmental Conservation
Hudson Valley Regional Council

Cover: Photograph by J. Goerg (NYSDEC) looking north showing Hudson River at Bear Mountain Bridge (center, river mile 46.7) and Iona Island (right) on April 7, 1989

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By M. Peter de Vries and Lawrence A. Weiss

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Troy, New York
2001

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.59	square kilometer (km^2)
acre	0.40483	hectare (ha)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per second (gal/s)	0.0010515	liter per second (L/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	3,785	cubic meters per day (m^3/s)
	Density and pressure	
slugs per cubic foot ($slug/ft^3$)	515.4	kilograms per cubic meter (kg/m^3)
pounds per square inch (psi)	70.3089	centimeters of water (at 4˚C)
	Dispersion	
square feet per day (ft^2/d)	0.09290	square meters per day (m^2/d)
	Temperature	
degrees Fahrenheit (˚F)	(˚F-32)/1.8	degrees Celsius (˚C)
	Specific conductance	
micromhos per centimeter at 25˚ Celsius (µmho/cm)	1.00	microsiemens per centimeter at 25˚Celsius (µS/cm)
	Equivalent concentration terms	
microgram per liter (µg/L)	1.000	part per billion (ppb)
milligram per liter (mg/L)	1.000	part per million (ppm)
milligrams per liter (mg/L) X *F1* = milliequivalents per liter (meq/L)		
milligrams per liter (mg/L) X *F2* = millimoles per liter (mmol/L)		
	F1	*F2*
Chloride (Cl^-)	0.02821	0.02821
Sodium (Na^+)	.04350	.04350

Sea Level: In this report, “sea level” refers to the 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, formerly called Sea Level Datum of 1929.

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ABSTRACT

The Hudson River is being considered for use as a supplemental source of water supply for New York City during droughts. One proposal entails withdrawal of Hudson River water from locations near Newburgh, Chelsea, or Kingston, but the extent to which this could cause the salt front to advance upstream to points where it could adversely affect community water supplies is unknown. The U.S. Geological Survey (USGS) one-dimensional Branch-Network Dynamic Flow model (BRANCH) was used in conjunction with the USGS one-dimensional Branched Lagrangian Solute-Transport Model (BLTM) to simulate the effect of five water-withdrawal scenarios on the salt-front location.

The modeled reach contains 132 miles of the lower Hudson River between the Federal Dam at Troy and Hastings-on-Hudson (near New York City). The BRANCH model was calibrated and verified to 19 tidal-cycle discharge measurements made at 11 locations by conventional and acoustic Doppler current-profiler methods. Maximum measured instantaneous tidal flow ranged from 20,000 ft^3/s (cubic feet per second) at Albany to 368,000 ft^3/s at Tellers Point; daily-mean flow at Green Island near Troy ranged from 3,030 ft^3/s to 45,000 ft^3/s during the flow measurements. Successive ebb- and flood-flow volumes were measured and compared with computed volumes; daily-mean bias was -1.6 percent (range from -21.0 to +23.7 percent; 13.5 percent mean absolute error). Daily-mean deviation between simulated and measured stage at eight locations (from Bowline Point to Albany) over the 19 tidal-cycle measurements averaged +0.06 ft (range from -0.31 to +0.40 ft; 0.21 ft root mean square error, RMSE). These results indicate that the model can accurately simulate flow in the Hudson River under a wide range of flow, tide, and meteorological conditions.

The BLTM was used to simulate chloride transport in the 61-mi reach from Turkey Point to Bowline Point under two seasonal conditions in 1990—one representing spring conditions of high inflow and low salinity (April-June), the other representing typical summer conditions of low inflow and high salinity (July-August). Measured chloride concentrations at Bowline Point were used to drive the BLTM simulations, and data collected at West Point were used for calibration. Mean bias in simulated chloride concentration for the April-June 1990 (high flow) data (observed range from 12 to 201 mg/L [milligrams per liter]; 30 mg/L RMSE) was –16 mg/L, and mean bias for the July-August 1990 (low flow) data (observed range from 31 to 2,000 mg/L; 535 mg/L RMSE) was +126 mg/L. The salt front (saltwater/freshwater interface) on the Hudson River was defined as the furthest upstream location where the chloride concentration exceeded 100 mg/L. Data from August 1991 were used to evaluate solute transport between West Point and Poughkeepsie because a chloride concentration of 100 mg/L was not observed at Clinton Point in 1990. The BLTM then was used to simulate chloride concentrations at Chelsea Pump Station and Clinton Point. Regression equations, based on daily mean values of specific conductance measured at West Point, were used to estimate daily mean chloride concentrations at Chelsea Pump Station and Clinton Point for model analysis. Mean biases in BLTM-simulated daily mean chloride concentrations for August 1991 were –38 mg/L at Chelsea Pump Station (range from 189 to 551 mg/L; 103 mg/L RMSE) and –9 mg/L at Clinton Point (range from 53 to 264 mg/L; 62 mg/L RMSE).

Hypothetical withdrawals at (1) Newburgh, (2) Chelsea, (3) Chelsea and Newburgh, (4) Chelsea and Kingston, and (5) Kingston and Newburgh, were simulated to compute the effects of withdrawals on salt-front movement. Withdrawals of 300 Mgal/d from any combination of Chelsea or Newburgh could result in upstream movement of the salt front of as much as 1.0 mi, given an initial salt-front location between West Point and Rogers Point. Scenarios that included withdrawals at Kingston caused the greatest upstream salt-front movement. Simulation of a 90-day April-June high-flow period during which discharges at Green Island averaged 25,200 ft^3/s indicated that withdrawals of 1,939 Mgal/d (million gallons per day) at Chelsea Pump Station would not measureably increase chloride concentrations at Chelsea Pump Station under normal tidal and meteorological conditions, but withdrawals at twice that rate (3,878 Mgal/d) could increase the chloride concentration at Chelsea Pump Station to 250 mg/L.

INTRODUCTION

The Hudson River, which flows more than 300 mi from Wallface Ponds in the Adirondack Mountains of northern New York State to the Battery, the southernmost point of Manhattan Island in New York City (fig. 1), is one of New York State's major water resources. The tidal reach, which extends 153.7 mi from the Battery to the Federal Dam at Troy (figs. 1, 2), contains saline water as far north as **river mile**[1] (**RM**) 85, above the Battery, depending on freshwater flow, **tide stage**, channel geometry, and wind. The river has been used for shipping for more than 3 centuries and serves as a water supply for industries, communities, and private groups; it also provides recreation and is a spawning ground for many fish species, some of which are of interest to the Atlantic Coast commercial fisheries. It is a flyway for many species of migrating birds and provides unique habitats for endangered species of birds, turtles, and fish. As human demands for water supply, waste disposal, and recreation have increased, river management has become vital to minimize contamination of this resource.

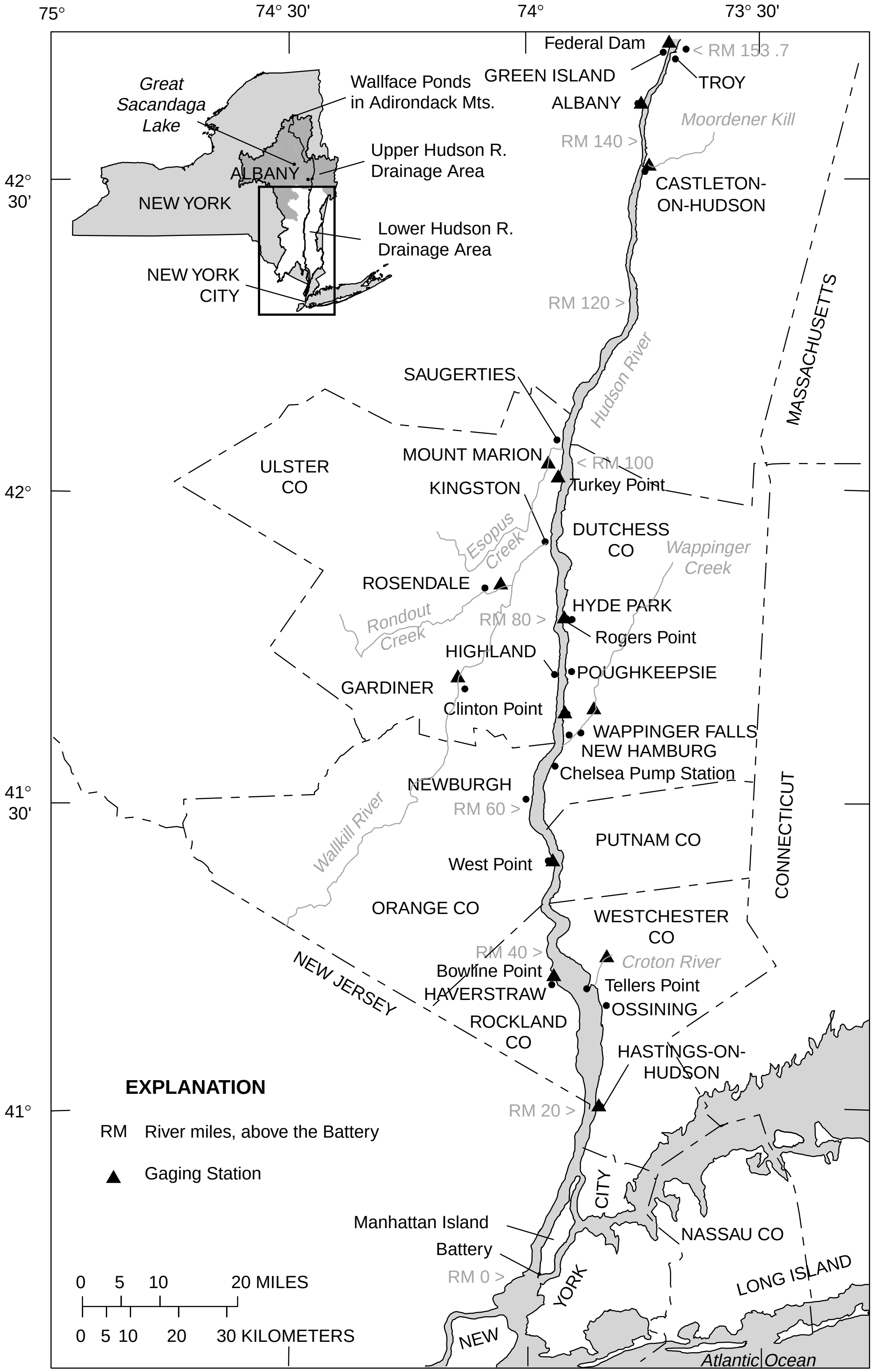
New York City's water-supply system serves more than 9 million people in the City and five nearby counties (fig. 1); several upstate communities can use the system during emergencies. Recent studies indicate that the present water-supply system cannot meet current demands during a drought (New York State, 1989). The Mayor's Intergovernmental Task Force on New York City Water Supply Needs convened in 1985 to review options for decreasing New York City's water demand and increasing water availability (New York City, 1992). Use of the tidal Hudson River is one option being explored as a supplemental source of water supply; but, a major concern is that the withdrawals might cause the **salt front** (saltwater/freshwater interface) to move upstream from its normal late-summer location south of Poughkeepsie and affect the Poughkeepsie water supply at river mile 77.2.

In 1988, the U.S. Geological Survey (USGS), in cooperation with the New York City Department of Environmental Protection, New York State Department of Environmental Conservation, and the Hudson Valley Regional Council (representing the lower Hudson Valley counties of Dutchess, Orange, Putnam, Rockland, Ulster, and Westchester [fig. 1]), began a 5-year study to evaluate the effect of hypothetical water withdrawals on the movement of the salt front. Computerized simulations described in this report are based on chloride concentrations and river-flow rates measured during the spring and summer of 1989, 1990, and 1991. **Specific-conductance** measurements were made during 1988-91 by boat to locate the salt front. Model simulations of flow and solute transport in the 132.2-mi reach between the Federal Dam at Troy and Hastings-on-Hudson (fig. 1) were run to indicate what effect hypothetical withdrawals at Chelsea, Kingston, and Newburgh would have on the position of the salt front. The study entailed:

(1) collection of specific conductance and tide-stage data at 15-minute intervals,
(2) measurement of river **discharge** at selected sites with an acoustic Doppler current profiler,
(3) delineations of salt-front position,
(4) compilation of Hudson River bathymetry data,
(5) calibration and verification of the flow and solute-transport models, and
(6) model simulation of hypothetical withdrawals.

The principal objectives were to implement, calibrate, and verify computerized flow and solute-transport models, then use a pair of **one-dimensional** models to simulate hypothetical public-supply

[1]Boldface terms are explained in glossary.



Base from U.S. Army Corps of Engineers, 1962

Figure 1. *Study area and major geographic features of the Hudson River estuary, N.Y., and locations of gaging stations.*

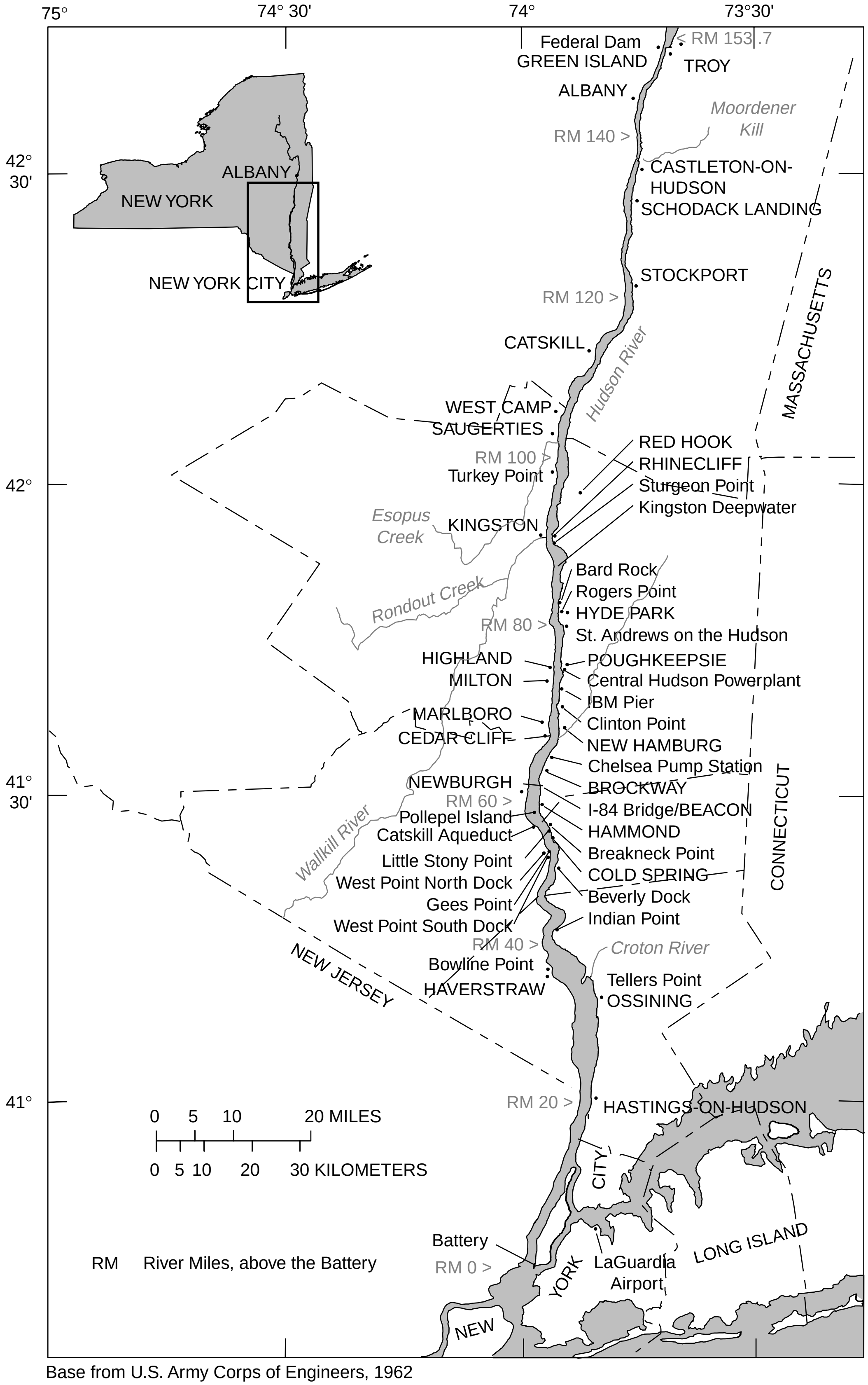


Figure 2. *Locations of additional geographical features of the Hudson River estuary, N.Y.*

withdrawals. This required compilation of bathymetry data for channel representation in the models and collection of tide-stage, specific conductance, and main-stem and tributary flow data for model calibration and verification. Regression analysis was used to relate specific conductance values measured at the tide gages to chloride concentration and salt-front location in ungaged areas.

Purpose and Scope

This report describes the study reach on the Hudson River, N.Y., and the procedures used to calibrate and verify the models. It also (1) describes the data-collection methods and the analytical procedures used to obtain data for model calibration and verification, (2) presents data on riverbed geometry, river flow, wind speed, and the specific conductance values that were used for the simulations, (3) summarizes the model boundary conditions and variables, (4) presents results of simulations of hypothetical supplemental withdrawals and of increased inflow, (5) describes results of a sensitivity analysis to identify which factors have the greatest effect on salt-front movement, and (6) discusses data measurement and model limitations. A tabulation of channel-geometry data and initial-condition input for a series of cross sections are given at the end of the report.

Acknowledgments

Special thanks are extended to the crews who helped during the tidal-cycle data-collection efforts day and night, regardless of weather, and to the following organizations for providing access to the river and use of facilities or land for instrument installation: U.S. Coast Guard at Saugerties, the Hidden Harbor Yacht Club, Roger's Point Boating Association, Mariner's Harbor, IBM Corporation, Lonestar Industries Clinton Point Trap-Rock Facility, White's Hudson River Marina, Newburgh Wastewater Treatment Facility, West Point Harbor Master's office at South Dock, Garrison Yacht Club, Orange and Rockland's Bowline Point Power Generating Facility, Stony Point Marina and Yacht Club, Croton Yacht Club, Croton Point Park, Tarrytown Marina, and Henry Green's Hastings Harbor Warehouses. Thanks also are extended to the employees of the Poughkeepsie Water-Treatment Plant, Castle Point Veterans Administration Hospital, Central Hudson's Danskammer Point Powerplant, New York City's Chelsea Pump Station, and Orange and Rockland Counties' Indian Point Powerplant, for participating in the sampling program and providing laboratory results.

HUDSON RIVER AND STUDY AREA

The Hudson River drains 13,370 mi^2 above its mouth at the Battery in New York City (fig. 1). More than 95 percent of the drainage basin is in New York State; the remainder lies in New Jersey, Vermont, Massachusetts, and Connecticut. The lower (tidal) Hudson River, which begins at the Federal Dam at Troy, is a drowned-rivermouth estuary in which the slope of the riverbed is extremely low (average 0.0002 ft/ft). Water velocities are sufficient, however, to carry suspended sediment seaward so that barrier islands do not form.

Study Area

The study included the entire lower Hudson River from the Federal Dam at Troy to the Battery, but the area of focus was the 77-mi reach from Turkey Point near Saugerties (RM 98.5) to Hastings-on-Hudson (RM 21.5), which normally includes the salt front and **transition zone**. Under normal seasonal tide and inflow conditions, the transition zone extends about 50 mi—from below Hastings-on-Hudson during high-flow periods in spring to New Hamburg (RM 67.7) during late summer low-flow periods (fig. 1). During the 1960's drought, however, saline water was observed as far north as Poughkeepsie, and in the dry summer of 1991, the salt front was detected at river mile 75.3 (1.9 mi below the Poughkeepsie water-treatment-plant intake and 1.2 mi below the Village of Highland water intake). A large inflow (82,500 ft^3/s) at Green Island in November 1990 caused the salt front to move downstream of the gage at Hastings-on-Hudson.

Chloride concentration can range widely within the study reach at any given time. For example, the chloride concentration at Clinton Point near New Hamburg (RM 70.3) is almost always low (less than 25 mg/L), whereas at Hastings-on-Hudson (RM 21.5) it is almost always relatively high (greater than 3,000 mg/L).

The width of the river within the study reach, as estimated from USGS topographic maps, ranges from about 600 ft near Albany to 18,000 ft near Haverstraw. Average bottom elevation of the **thalweg** is 60 ft below sea level; the lowest elevation is 225 ft below sea level near West Point. Channel geometry at six selected locations along the study reach are depicted in figure 3, further on.

Tidal and Nontidal Flow

The Hudson River is tidally affected as far upstream as the Federal Dam near Troy (RM 153.7). Water below this location can flow both upstream (**negative flow**) and downstream (**positive flow**), depending on the tidal conditions. Tide stage within the tidal part of the river, as calculated for the period of record for each of the following five sites, has a mean daily range of about 4.1 ft at Hastings-on-Hudson (RM 21.5), about 3.9 ft at Bowline Point (RM 37.5), about 3.6 ft at West Point (RM 51.6), about 4.3 ft at Turkey Point (RM 98.5), and about 5.5 ft at Albany (RM 146.0)(fig. 1). This variability is primarily due to differences in channel geometry and cross-sectional area. Maximum instantaneous tidal flows range from ±20,000 ft^3/s (12,900 **Mgal/d**) at Albany to about ±400,000 ft^3/s (259,000 Mgal/d) at Tellers Point (RM 33.9), 0.8 mi upstream from Ossining (fig. 1), when freshwater inflow at Green Island is 6,000 ft^3/s (3,870 Mgal/d). Tidal flows as great as 368,000 ft^3/s (238,000 Mgal/d) were measured during August 22-23, 1990 at Tellers Point.

Freshwater inflow, as measured at the USGS gage at Green Island (RM 153.7), comes mostly from the upper Hudson River (the reach above Troy) (fig. 1). Gaged tributaries along the lower Hudson River are the Moordener Kill (RM 138.0), Esopus Creek (RM 102.7), Rondout Creek (RM 91.5), Wallkill River (RM 91.5), Wappinger Creek (RM 67.3), and Croton River (RM 33.5). Inflows from these tributaries were used as an index of freshwater flow for this study and represent 10,179 mi^2 or 77 percent of the 13,265-mi^2 drainage area at Hastings-on-Hudson.

Salt Front

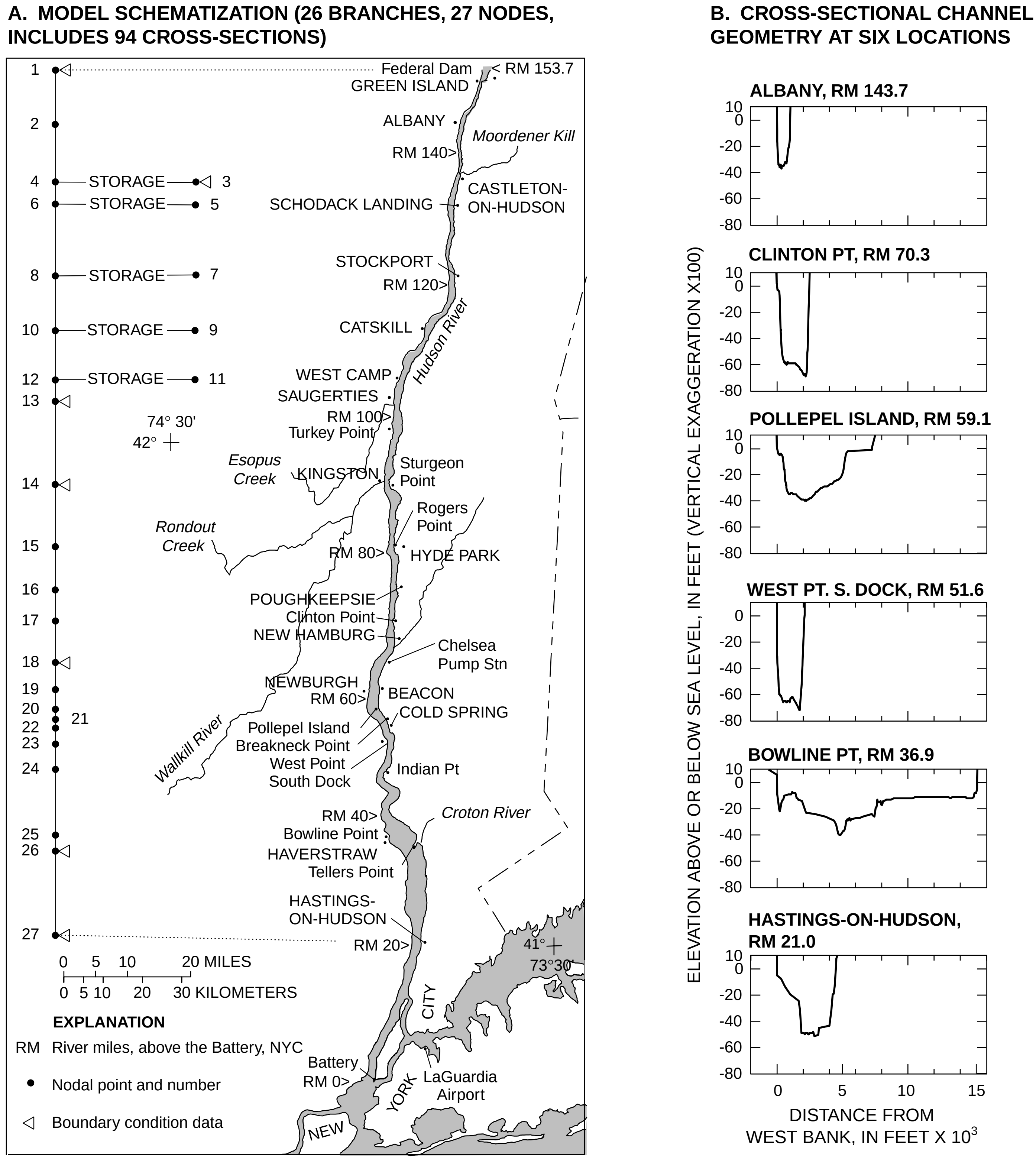
Although a vast amount of information about Hudson River flow has been collected over the years, several aspects pertaining to the lower Hudson River remain poorly understood. One of these is the movement of saline water, which can adversely affect water supplies, wildlife habitat, and fisheries (Busby, 1966; Giese and Barr, 1967; Darmer, 1969; Harleman and others, 1972; Quirk and others, 1973; Abood, 1974; Abood, 1977; Horne, 1977a; Horne, 1977b; Abood, 1978; Apicella and Zimmie, 1978; Dunn and Gravlee, 1978; Horne, 1978; Embree and Wiltshire, 1978. Hudson River Research Council, 1980; Stedfast, 1980; Turk and Troutman, 1981; Stedfast, 1982; Bokuniewicz and Flood, 1986; Malcolm Pirnie, 1986; New York City, 1986; Darmer, 1987; Lee, 1987; New York State, 1987; Rohmann and Lilienthal, 1987; Hahl, 1988; New York State, 1988; de Vries and Freeman, 1991; Abood and others, 1992; Thatcher, 1992; and Weiss and others, 1994).

The salt front is defined in this report (unless otherwise noted) as the location at which the chloride concentration equals 100 mg/L, equivalent to a specific conductance of 500 μS/cm. The 250-mg/L New York State drinking-water standard for chloride (New York State, 1991) is a Secondary Standard (U.S. Environmental Protection Agency, 1994), meaning that chloride at this concentration is primarily a taste and odor problem rather than a health issue. Lower concentrations can affect water use, however; industrial users and people on salt-restricted diets may define a concentration as low as 50 mg/L as a quality criterion.

Various factors affect the movement of the salt front; the main ones are freshwater flow (discharge), the twice-daily tide, channel geometry, and wind, especially when parallel to the river. Large changes in barometric pressure and, more significantly, sustained winds along the continental shelf, also can affect the tide stage and, thus, the movement of the salt front (Milton Rutstein, National Ocean Service, 1989, oral commun.).

MODELING APPROACH

The modeling approach entailed (1) selection of models consistent with the Hudson River's hydraulic characteristics and channel conditions, (2) compilation of available flow and stage data and collection of salinity data, (3) developing relations between values of specific conductance (measured continuously) and chloride concentrations in ungaged areas, and (4) model calibration and sensitivity analysis.



Base from U.S. Army Corps of Engineers, 1962

Figure 3. *Schematization of the lower Hudson River, N.Y., for the Branch-Network Dynamic-Flow model. (A) Model schematization showing nodal point numbers, storage areas, and boundary condition data locations. (B) Cross-sectional channel geometry at six selected locations between Green Island and Hastings-on-Hudson. (Additional schematization details are given in tables 10 and 11 and appendix* I *and* II.*)*

Model Selection

Various criteria were considered during model selection, these included the physical and hydraulic characteristics of the Hudson River, the objectives of the study, and the models' availability and ease of use. Several one-dimensional flow and solute-transport models were considered.

Because the lower Hudson River has an extremely low slope as well as daily flow reversals and tidal effects, it requires use of a **fully dynamic flow** model. Most surface-water flow models are based on two equations— the **continuity equation**, which solves for the conservation of mass (Newton's first law), and the **dynamic equation**, which solves for the conservation of momentum (Newton's second law). The dynamic equation is often simplified where **uniform-flow conditions** and(or) **steady-flow conditions** prevail, but because neither condition applies to the lower Hudson River, the number of appropriate models was limited.

Branch-Network Dynamic Flow Model

A modeling study of Hudson River flow was done in the late 1960's by Harleman and others (1972) and Malcolm Pirnie (1986) with the Massachusetts Institute of Technology (MIT) Transient Salinity Intrusion Model (TSIM) (Thatcher and Harleman, 1972a, 1972b, 1978), which solves the continuity, dynamic, and conservation equations through a **finite-difference** solution scheme. The model selected for the present (1989-91) study was the Branch-Network Dynamic Flow model (BRANCH) (Schaffranek and others, 1981; Schaffranek, 1987), which had been used by the USGS to simulate flow in the reach from Albany to Clinton Point (Stedfast, 1982; Stedfast, 1989). The BRANCH flow model meets most of the requirements for the river's physical conditions and is well documented and readily available; it also has a data-management system (Lai and others, 1978; Schaffranek and Baltzer, 1978) and is easily transported among computers. It is similar to the MIT model except that the solute-transport function is provided by a separate solute-transport model. The BRANCH model solves the unsteady-flow equations (continuity and dynamic) through a four-point, nonlinear, implicit finite-difference solution scheme. The unsteady-flow equations account for nonuniform velocity distribution in the cross section, including terms for the Boussinesq coefficient, flow conveyance and storage separation, lateral flows, pressure differentials that result from density variations, and wind effects.

Branched Lagrangian Solute-Transport Model

The model selected for the solute-transport function was the Branched Lagrangian Solute-Transport Model (BLTM) (Schoellhamer, D.H., and Jobson, H.E., 1986a, 1986b; Jobson, 1987; Jobson and Schoellhamer, 1987) because a solution scheme that reduces numerical dispersion inherent in **Eulerian-based models** is used in BLTM. The BLTM solves the convective-dispersion equation through a Lagrangian reference frame that moves the computational nodes with the flow and can simulate the movement and fate of as many as 10 water-quality constituents for the BRANCH-computed **unsteady-flow distribution**. This model is also highly transportable between computers, is well documented, and can use the same data-management system as the BRANCH model.

Once flows had been generated by the flow model at 15-minute intervals, they were transformed into daily values and used as input to the solute-transport model. Calibration of BLTM was done by adjusting the chloride-dispersion values for each reach until the model results closely matched the observed daily mean chloride values. Daily mean values (as opposed to 15-minute or other time-interval values) were chosen because (1) daily mean values reflect primarily low-frequency events such as spring-tide or neap-tide cycles and the river's response to inflows, which are the major factors in movement of the salt front, whereas 15-minute data include mainly the more frequent (semidiurnal) tides and wind effects; (2) regressions that relate predicted to measured salt-front location, as calculated from the West Point index gage, display best fit when based on daily mean values (regressions based on extreme semidiurnal values such as daily maximum or daily minimum display poorer fits); and (3) trends in daily mean chloride values based on a 24-hour time-step are reasonably close to those based on a tidal-day time-step of 24 hours 50 minutes.

The BRANCH flow model and BLTM solute-transport model were calibrated and verified to quantify the forces that control saltwater movement in the lower Hudson River (the reach between Albany and Hastings-on-Hudson) and to predict the locations to which the salt front would move in response to specified stresses (withdrawals and drought conditions). The models were calibrated and verified from data collected before 1980 and from June 1989 through August 1991.

Data

Data needed as input to the flow and transport models include river stage (water-surface elevation), main-stem discharge at Green Island, inflow from tributaries, wind velocity and direction, and salinity. Most simulations represented the range of tide and freshwater-flow conditions measured from May 1989 through October 1990 and in August 1991, but some incorporated data from 1979 to 1980 and from the drought during the 1960’s, the most severe drought on record.

Stage, Inflow, and Wind Velocity

Available data for the tidal part of the Hudson River consisted of (1) continuous and partial-record stage data from 11 locations, (2) flow data from 11 sites in addition to Green Island, and (3) inflow data from five tributaries. Locations are described in table 1; discharges on selected dates are listed in table 2. Wind-velocity data were available from Albany and LaGuardia Airports (fig. 2).

Tide Stage and Flow Measurements

Tide-stage data were collected at 15-min intervals from June through October of 1989 and 1990 at the stations listed in table 3; which also indicates the types of recording devices and the reference-point locations and datum corrections. Standard USGS procedures for measuring stage (Carter and Davidian, 1969) and leveling measuring points into a common **datum** (Kennedy, 1988) were followed. Gage-height corrections caused by drift in the pressure transducers used to measure stage are given in table 4.

Flow measurements in the tidal reaches of the Hudson River were made from a boat by a RD Instruments[2] Acoustic Doppler Current Profiler (ADCP) (Gordon, 1989; RD Instruments, 1989; Simpson and Oltmann, 1990). All ADCP measurements were made between June 1989 and October 1990. Measurements were made over a 22-hour period because a 6- to 8-hour model startup time was required before simulation was considered valid. Measurements used for calibration are given in table 2; some of these were collected in previous studies of 1965-67 (Giese and Barr, 1967; Busby and Darmer, 1970) and 1979-80 (Stedfast, 1982) and were measured with current meters from bridges or the moving-boat method (Smoot and Novak, 1969).

Salinity

The term salinity, as used in this report, refers to the concentration of chloride (as sodium chloride) derived from the ocean. **Specific conductance**, a measure of a fluid’s ability to conduct an electrical current, is an indicator of total dissolved solids and can be directly related by regression analysis to salinity within the concentration ranges found in the Hudson River estuary. (See section, "Relation of Specific Conductance to Chloride Concentration".) Because the reach upstream from the salt front has a relatively low dissolved solids concentration, elevated specific conductance readings are a reliable indication of the salt front’s presence.

A total of 30 boat runs, hereafter referred to as salt-front delineations, were made between April and October of 1988-91 between Teller’s Point (RM 34) and the Poughkeepsie Water-Treatment Plant (RM 77.2) to locate the salt front. During each salt-front delineation, specific conductance was recorded with a Hydrolab Scout (Hydrolab Corporation, 1988) at three verticals in each cross section and at three depths at each vertical, and samples were collected for analysis at the USGS National Water Quality Laboratory in Denver, Colo. Some typical distribution patterns of specific conductance in relation to depth at Bowline Point, West Point, Clinton Point, and Poughkeepsie are plotted in figure 4.

Salinity data were collected at 15-minute intervals with a USGS Minimonitor (Gordon and Katzenbach, 1983) at Turkey Point near Saugerties (RM 98.5), Rogers Point near Hyde Park (RM 81.0), Clinton Point near New Hamburg (RM 70.3), West Point (RM 51.6), Bowline Point at Haverstraw (RM 37.5), and Hastings-on-Hudson (RM 21.5) (fig. 1) during 1989-90; data were collected only at West Point in 1991 because data collection at the other gages had been discontinued.

Data collected in this study were used to develop regression equations that were in turn used to compute (1) chloride concentration from specific conductance, (2) chloride concentrations at Chelsea Pump Station and Clinton Point from specific-conductance values at West Point, (3) salt-front location from specific conductance at West Point and

[2]Use of trade and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Table 1. *Locations of sites on the Hudson River, N.Y., from which stage and flow data were measured for BRANCH flow model*

[Locations are shown in figs. 1 and 2. °, degrees; ′, minutes; ″, seconds; mi^2, square miles]

Station location and drainage area

Station location	Station number	Latitude ° ′ ″	Longitude ° ′ ″	Drainage area (mi^2)	River mile[a]
Green Island	01358000[b]	42 45 08	73 41 22	8,090	0.00
Albany	01359139[c]	42 38 53	73 44 50	8,288	8.53
Catskill	01361450[b]	42 12 36	73 51 12	9,336	41.42
West Camp	01362187[d]	42 06 46	73 55 34	10,026	49.12
Turkey Point	01364832[d]	42 00 50	73 56 22	10,506	55.92
Red Hook	01364840[b]	41 59 58	73 56 44	10,509	56.92
Rhinecliff	01372009[c]	41 55 10	73 57 12	10,528	62.72
Sturgeon Point	0137200910[b]	41 54 06	73 57 16	11,700	64.22
Bard Rock	0137203901[d]	41 48 16	73 57 02	11,769	71.32
Rogers Point	0137204020[d]	41 46 23	73 56 55	11,804	73.52
Poughkeepsie	01372055[c]	41 42 08	73 56 29	11,732	78.63
Clinton Point	01372059[d]	41 37 24	73 56 55	11,745	84.23
Newburgh/Beacon	01372575[b]	41 30 18	73 59 21	12,011	93.23
West Point	01374019[c]	41 23 10	73 57 20	12,596	102.86
Beverly Dock	0137402390[b]	41 21 46	73 57 26	12,603	104.34
Indian Point	01374320[b]	41 16 00	73 58 36	12,730	113.06
Bowline Point	0137448530[d]	41 12 12	73 57 22	12,792	117.56
Tellers Point	01374486[b]	41 10 09	73 53 59	12,800	120.66
Hastings-on-Hudson	01376303[d]	40 59 35	73 53 12	13,265	133.00

Tributary location

Stream name	River mile[a]	Latitude ° ′ ″	Longitude ° ′ ″
Moordener Kill[b]	15.93	42 32 36	73 45 13
Esopus Creek[b]	51.92	42 04 15	73 55 49
Rondout Creek[b] (Combined Rondout/ Wallkill)	62.82	41 55 19	73 58 08
Wappinger Creek[b]	87.23	41 34 55	73 56 52
Croton River[b]	120.76	41 10 25	73 53 05

[a] River mile downstream from Federal Dam at Green Island. (Green Island is 153.7 river miles upstream from the Battery in New York City.)
[b] Discharge data available.
[c] Discharge and stage data available.
[d] Stage data available.

Table 2. *Hudson River discharge measurements used for calibration of BRANCH flow model*

[Locations are shown in fig. 2. Data for measurements of 1965-80 from Stedfast (1982). ˚F, degrees Fahrenheit; discharges are in cubic feet per second; -, upstream (tidal) flow; +, downstream flow]

Date	*Water temperature (˚F)*	*Average discharge at Green Island*	*Modeled reach*	*Measurement locations*	*Discharge*	
					Maximum upriver (northward)	*Maximum downriver (southward)*
Aug. 11, 1965	77	3,030	Green Island to Clinton Point	Poughkeepsie	-245,000	+237,000
May 24-25, 1966	58	20,000	"	"	-238,000	+281,000
Aug. 30, 1966	74	4,810	"	"	-225,000	+231,000
June 21-22, 1967	71	6,370	"	Rhinecliff Poughkeepsie	-220,000 -318,000	+208,000 +280,000
Aug. 21, 1979	77	6,000	"	Albany Red Hook Poughkeepsie	-19,100 -163,000 -239,000	+19,800 +174,000 +239,000
Mar. 26, 1980	36	39,000	"	Albany	+28,200	+50,000
Apr. 18, 1980	48	26,000	"	Catskill	-117,000	+153,000
June 13-14, 1989	70	19,600	Albany to Haverstraw	Indian Point	-134,000	+205,000
July 18-19, 1989	75	7,500	Green Island to Haverstraw	Beverly Dock	-200,000	+260,000
Aug. 22-23, 1989	76	5,600	"	Newburgh/ Beacon	-200,000	+193,000
Sept. 26-27, 1989	75	11,500	Green Island to Hastings-on-Hudson	"	-210,000	+224,000
May 9-10, 1990	56	17,500	"	Indian Point	-267,000	+295,000
June 13-14, 1990	70	7,400	"	Poughkeepsie	-255,000	+266,000
July 18-19, 1990	75	5,500	"	West Point	-250,000	+285,000
Aug. 22-23, 1990	76	6,000	"	Tellers Point	-340,000	+368,000
Oct. 23, 1990	57	18,000	Green Island to West Point	Sturgeon Point	-190,000	+217,000
Oct. 24, 1990	57	45,000	"	"	-110,000	+237,000

Table 3. *Location, type of stage-recording device, and reference point information for tide-stage recorders in Hudson River, N.Y., 1989-90*

[Locations are shown in fig. 1. psi, pounds per square inch]

		Reference Point Information		
Station number	*Stage-recording device*	*Location*	*Elevation (feet above sea level)*	*Datum corrections[1] (feet)*
01359139	Fischer-Porter ADR and float in well	Corning Preserve in Albany—Top of I-beam support for outside staff gage	0.82	-10.00
01364832	Campbell CR10 data logger and Druck PDCR 830 pressure transducer, differential 0 to 5 psi	Turkey Point—Lag bolt in piling at southeast corner of dock lighthouse	5.68	-0.55
0137204020	Campbell CR10 data logger and Druck PDCR 830 pressure transducer, differential 0 to 5 psi	Rogers Point—Lag bolt in west face ledge 2 ft west of navigation light	6.05	+0.04
01372059	Campbell CR10 data logger and Scientific Instruments bubble gage with Druck PDCR 830 pressure transducer, differential 0 to 5 psi	Clinton Point—File mark in steel rail of walkway to pump at quarry	15.15	-0.06
01374019	Campbell CR10 data logger and Druck PDCR 830 pressure transducer, differential 0 to 5 psi	South dock at West Point—Lag bolt in piling at northeast corner of South Dock	6.12	-0.12
0137448530	Campbell CR10 data logger and Druck PDCR 830 pressure transducer, differential 0 to 5 psi	Bowline Point—Three file marks in steel decking of pier and 100 ft south of platform	8.42	-0.08
01376303	Campbell CR10 data logger and Druck PDCR 830 pressure transducer, differential 0 to 5 psi	Hastings-on-Hudson—Top of bolt in bracket holding transducer pipe	5.99	0.00

[1]Datum corrections to be applied to stage data stored in the time-dependent data base.

Table 4. *Stage corrections applied to 1989-90 Hudson River, N.Y., tide-stage data used in BRANCH flow model*

[Station locations are shown in fig. 1. All values are in feet. Dash indicates no correction]

Period		*Station Number and Location*				
From	*To*	*013704020 Rogers Point*	*01372059 Clinton Point*	*01374019 West Point*	*0137448530 Bowline Point*	*01376303 Hastings-on-Hudson*
9-21-89	10-17-89	0.00	-0.15	0.00	-0.14	-0.14
4-11-90	4-30-90	--	--	0.00	-0.14	-0.14
4-31-90	5-18-90	0.00	-0.09	0.00	-0.15	-0.15
5-19-90	6-14-90	0.00	--	0.00	-0.15	-0.15
6-15-90	8-13-90	--	--	0.00	-0.16	-0.19
8-22-90	10-11-90	--	--	0.00	-0.14	-0.30
10-12-90	10-22-90	0.00	--	0.00	-0.14	-0.14
10-23-90	11-15-90	--	-0.09	0.00	--	-0.22

Hastings-on-Hudson, and (4) salt-front location from tide levels at West Point and inflows at Green Island and five tributaries. Results are discussed below.

Relation of Specific Conductance to Chloride Concentration

Specific conductance values and chloride concentrations of more than 1,030 samples collected from the lower Hudson River during 1988-90 were used to develop a regression equation that relates specific conductance to chloride concentration. The equation of best fit (coefficient of determination is 0.9987) is

$$y = -63 + 0.2925x + 4.071\times10^{-8}x^{2.5} - 1.413\times10^{-10}x^{3} + \frac{870\ln(x)}{x} , \qquad (1)$$

where

y = chloride concentration, in milligrams per liter; and
x = specific conductance, in microsiemens per centimeter at 25 degrees Celsius.

The correlation between specific conductance and chloride concentration, as determined through regression of data from 1,033 water samples, is illustrated in figure 5.

Relation of Chloride Concentrations at West Point to Those at Chelsea and Clinton Point

The daily-mean specific conductance values computed for Bowline Point and West Point were converted to chloride concentration through equation 1. Because no continuous specific conductance data were collected in the reach above West Point during August 1991 (the only period during the study that the salt front moved north of the bay at Newburgh, RM 56.2-67.7), specific conductance measurements made during salt-front delineations between West Point and the Poughkeepsie Water-Treatment Plant were used to relate daily mean chloride concentration at West Point to daily mean chloride concentrations at Chelsea Pump Station (RM 66.2) and Clinton Point (RM 70.3) through the following regression equations:

$$\text{Chelsea:} \quad y = \frac{x^{1.69}}{598} - 150 , \qquad (2a)$$

$$\text{Clinton Point:} \quad y = \frac{x^{1.829}}{2838} - 150 , \qquad (2b)$$

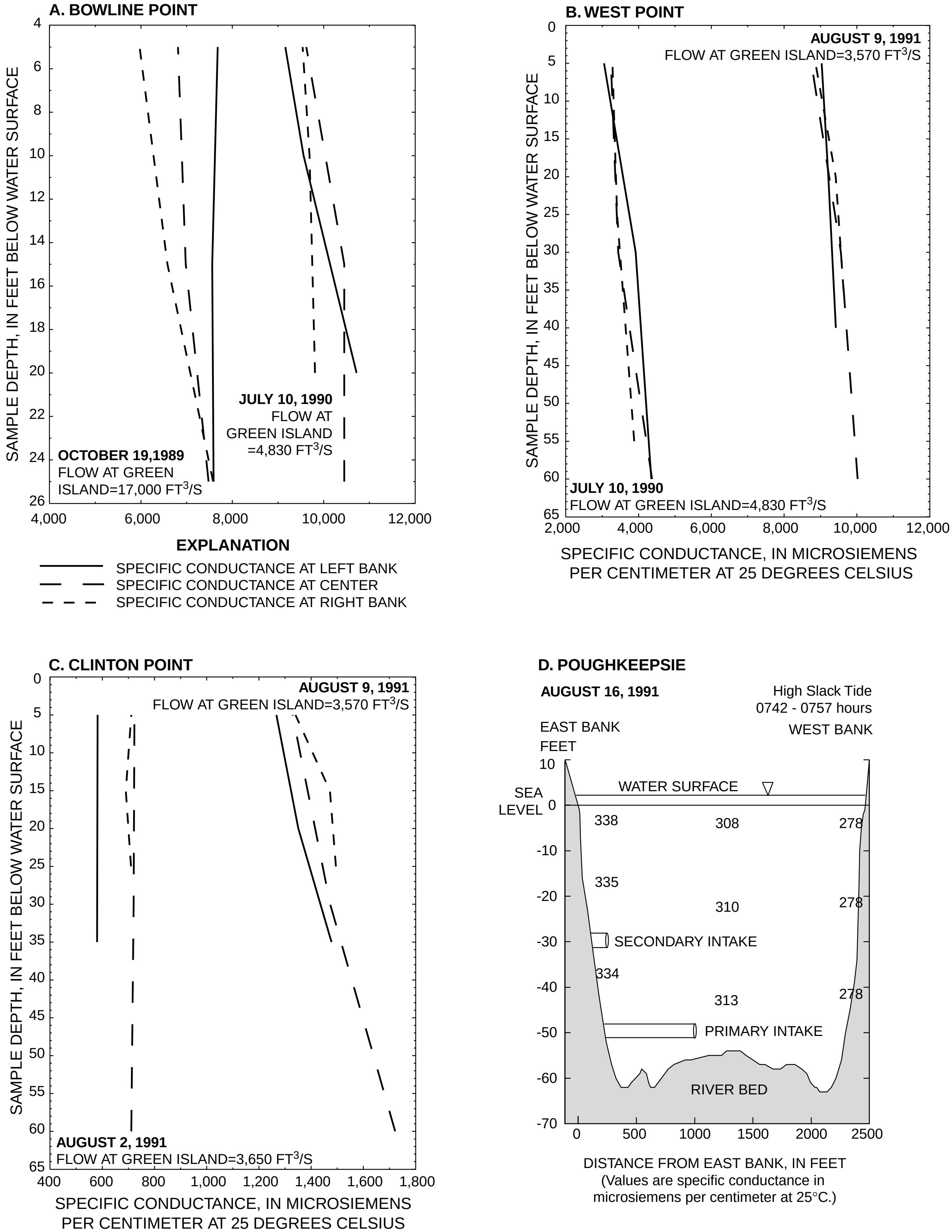
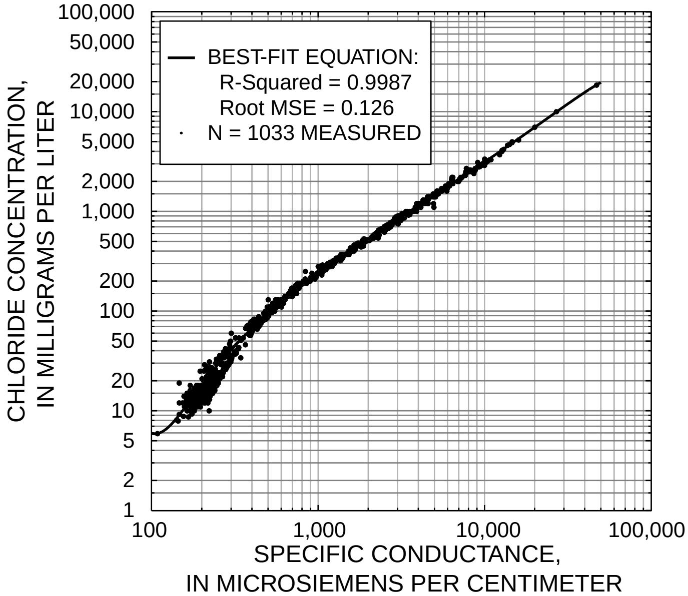


Figure 4. *Relation between sample depth and specific conductance at left bank, center, and right bank of Hudson River, N.Y., on selected dates, 1989-91: A. Bowline Point. B. West Point. C. Clinton Point. D. Poughkeepsie.*



BEST-FIT EQUATION:
$Cl = A + B(Sp) + C(Sp^{2.5}) + D(Sp^3) + (E\ln(Sp))/Sp$
WHERE:
Cl= Chloride Concentration, in milligrams per liter
Sp= Specific Conductance, in microsiemens per centimeter at 25 degrees Celsius
A= -63
B= 0.2925
C= 4.071×10^{-8}
D= -1.413×10^{-10}
E= 870

Figure 5. *Relation between specific conductance and chloride concentration in the lower Hudson River, N.Y., based on analyses of 1,033 water samples collected prior to 1991.*

where

y = daily mean chloride concentration at Chelsea Pump Station or Clinton Point, in milligrams per liter; and

x = daily mean chloride concentration at West Point, in milligrams per liter.

The coefficients of determination for Chelsea Pump Station and Clinton Point equations were 0.897 and 0.943, respectively, and the standard errors of estimate were ±9.6 and ±7.7 percent, respectively. Computed daily means for August 9-31, 1991, are shown in table 5.

To verify the predictions of the solute-transport model (described later in the report) at a variety of locations, specific conductance at West Point was related to chloride concentration at West Point (RM 51.6), Catskill Aqueduct at Breakneck Point (RM 56.2), Newburgh (RM 62.3), Chelsea Pump Station (RM 66.2), and Clinton Point (RM 70.3). The regression equations are shown in table 6A; another set of equations (table 6B) was used to recreate the daily chloride concentration at 3 sites near Poughkeepsie—the IBM pier (RM 72.3), the Central Hudson powerplant (RM 74.8), and at the Poughkeepsie Water-Treatment Plant (RM 77.2).

Relation of Specific Conductance at Hastings-on-Hudson and West Point to Salt-front Location

Regression equations were developed that relate daily mean specific conductance at the Hastings-on-Hudson or West Point gages to the salt-front locations observed in the 1988-91 salt-front delineations. The resulting equation for Hastings-on-Hudson is

$$SFRM_{100} = -3911.77 + 193.59\ln(SCHH) + \frac{21635.3}{\ln(SCHH)} - \frac{16820.5}{\sqrt{SCHH}} \quad (3)$$

where

$SFRM_{100}$ = 100 mg/L salt-front location at high slack tide, in river miles; and

$SCHH$ = Daily mean specific conductance at Hastings-on-Hudson, in microsiemens per centimeter at 25 degrees Celsius.

The equations for West Point are shown in table 7.

The standard error of estimate was 4.0 mi. The curve flattens at RM 35 (fig. 6a), most likely because lateral mixing in the bay at Haverstraw (RM 33.8-40.7) increases as a result of the extreme width (up to 3.5 mi) and shallow depths (about 20 ft); this mixing decreases the rate of salt-front advancement in relation to its rate in narrower reaches.

The measured specific conductance values at West Point (RM 51.6) were used to delineate the salt front upstream of that gage because the bay at Haverstraw appears to have a strong effect on mixing and, hence, the rate of salt-front movement, and therefore would give more reliable results than the Hastings equation. The resulting lines of fit for the 100-, 250-, and 500-mg/L salt fronts based on West Point data are shown in figure 6B; the equations and standard errors of estimate are given in table 7. The standard error of estimate for the 100-mg/L equation is 4.0 mi if calculated from the Hastings-on-Hudson equation (eq. 3 and fig. 6A) and is 1.45 mi if calculated from the West Point equation (table 7 and fig. 6B).

Table 5. *Observed chloride concentration in Hudson River at West Point, and computed concentrations at Chelsea Pump Station and Clinton Point, N.Y., August 9-31, 1991*

[Locations are shown in fig 1. Concentrations are in milligrams per liter]

Date (August 1991)	*Observed concentrations at West Point*	*Computed concentrations*	
		Chelsea Pump Station	*Clinton Point*
9	2,171	551	264
10	1,998	484	231
11	1,887	421	184
12	1,874	413	178
13	1,844	398	167
14	1,809	445	216
15	1,664	287	121
16	1,730	340	129
17	1,790	369	148
18	1,672	312	112
19	1,509	243	74
20	1,527	250	78
21	1,436	212	61
22	1,488	298	79
23	1,471	228	67
24	1,640	303	104
25	1,663	308	110
26	1,526	254	78
27	1,434	189	53
28	1,462	201	53
29	1,490	236	71
30	1,430	213	60
31	1,332	179	45

Relation of Tide Levels at West Point and Inflows to Salt-front Location

Physical factors that affect chloride transport include stream geometry, freshwater inflows, ocean tides, and wind velocity. Antecedent conditions also must be considered in any attempt to develop longitudinal concentration profiles. A regression equation (eq. 4) developed by Cooper and others (1988) can be used to approximate chloride concentrations from freshwater inflows and maximum tidal effect, given present channel geometry, wind velocities less than 5 mi/h, and initial water density of 1.939 slug/ft^3 (freshwater). Water levels at West Point were used to evaluate tidal effect; the initial water density for the 17 observations of the 100-mg/L chloride-concentration location (based on specific-conductance data) was about 1.939 slug/ft^3 at West Point. The mean elevation of the five previous daily maximum high tides (5-day mean) was used to approximate steady-state conditions, and, similarly, the 5-day mean inflow was computed as the average of the sum of the five previous daily mean flows at Green Island plus those of the five tributaries (Moordener Kill, Esopus Creek, Rondout Creek, Wallkill River, and Wappinger Creek [fig. 1]). The resulting equation for the 100-mg/L chloride-concentration location (*ClL*) upstream from West Point at high slack tide, in river miles, is

$$ClL = \frac{877 tidemax^{0.38}}{flow^{0.34}} , \qquad (4)$$

where

ClL = river mile for 100-mg/L chloride concentration,

tidemax = 5-day mean maximum tide, in feet above mean sea level, and

flow = 5-day mean inflow, in cubic feet per second.

The coefficient of determination was 0.76, and the standard errors of estimate were +5.5 and –6.6 percent. This equation has a mean bias of 2.4 mi and a RMSE of 5.9 mi. The observed and calculated salt-front locations are listed in table 8. Wind during major storms affects the river stage and could alter the results of the empirically derived relation between salt-front location and flow. Wind velocity could be incorporated into the equation, but using the 5-day prior average maximum tide would obscure its short-term effect because storm-related wind rarely persists longer than a day. An estimate of stage for the day of the storm could be provided by replacing the 5-day value with the maximum tide for the day of the storm.

Application of Salinity Equations to Recent and Historical Data

Estimates of the location of the 100-mg/L chloride concentrations, based on equation 4, matched the observed location within 1.8 mi for July 1993 and

Table 6. *Equations relating daily mean chloride concentration in Hudson River upstream from West Point to daily mean specific conductance at West Point, N.Y.*

[Locations are shown in fig. 2. r^2, coefficient of determination; Sxy, standard error of estimate; SpC, daily mean specific conductance; µS/cm, microsiemens per centimeter at 25 degrees Celsius; Cl, daily mean chloride concentration, in milligrams per liter (mg/L); RM, river mile above the Battery at New York City; --, not enough data to determine]

Location and river mile	Equation	r^2	Standard error of estimate (percent)		Minimum daily mean specific conductance for given chloride concentration	
			Max	Min	Cl (mg/L)	SpC (µS/cm)
A. Equations based on regression analyses of field data:						
West Point (RM 51.6)	$Cl = -15 + 0.213SpC^{1.09}$	0.978	+15.8	-13.7	100	320
Catskill Aqueduct (RM 56.2), at Breakneck Point	$Cl = -50 + 0.142SpC^{1.09}$	.990	+ 9.6	- 8.8	100	600
Newburgh, I-84 (RM 62.3)	$Cl = -170 + 0.088SpC^{1.09}$	.951	+11.7	-10.5	100	1,580
Chelsea Pump Station (RM 66.2)	$Cl = -192 + 0.051SpC^{1.09}$	.736	+23.3	-18.9	100 250 500	2,800 4,100 6,200
Clinton Point (RM 70.3)	$Cl = -285 + 0.035SpC^{1.09}$	.618	+17.0	-14.6	100	5,100
B. Equations derived from following relation: $Cl = -Constant + bfactor \times SpC^{1.09}$, where: $Constant = -765 + 14.82\ RM$, and $bfactor = 98.237 + 2.2016 \times \ln(RM) - 902.392/\ln(RM) + 877.24/(RM)^{0.5}$						
IBM pier (RM 72.3), below Poughkeesie	$Cl = -306 + 0.032SpC^{1.09}$	--	--	--	100	5,850
Central Hudson Power-plant (RM 74.8), near Poughkeepsie	$Cl = -348 + 0.030SpC^{1.09}$	--	--	--	100	6,750
Poughkeepsie Water-Treatment Plant (RM 77.2)	$Cl = -379 + 0.029SpC^{1.09}$	--	--	--	100 250 500	7,420 9,500 13,000

0.2 mi for August 1993 (both were periods of high chloride concentrations at West Point). On July 21, 1993, when the daily mean specific conductance at West Point was 6,590 µS/cm, the observed and computed locations of the 100-mg/L chloride concentrations were RM 73.5 and RM 75.3, respectively. On August 19, 1993, the daily mean specific conductance at West Point was 6,380 µS/cm, and the observed and computed locations of the 100-mg/L chloride concentrations were RM 74.5 and 74.7, respectively. The 100-mg/L chloride-concentration equation indicates that a daily mean specific conductance of at least 7,350 µS/cm at West Point would be required for the 100-mg/L chloride concentration to reach the Poughkeepsie water-treatment plant (RM 77.2); this concentration would be equivalent to a daily mean chloride concentration of 643 mg/L at Chelsea Pump Station.

Table 7. *Equations relating salt-front location in the Hudson River to daily mean specific conductance at West Point, N.Y.*

[µS/cm, microsiemens per centimeter at 25 degrees Celsius]

EQUATIONS

A. $SFRM_{100} = -4{,}840 + 237.2 \times \ln(SCWP) + 27{,}193/\ln(SCWP) - 21{,}347/(SCWP)^{0.5}$

B. $SFRM_{250} = -9{,}035 + 422.0 \times \ln(SCWP) + 52{,}140/\ln(SCWP) - 43{,}392/(SCWP)^{0.5}$

C. $SFRM_{500} = -19{,}673 + 877.9 \times \ln(SCWP) + 117{,}001/\ln(SCWP) - 104{,}392/(SCWP)^{0.5}$

where: *SFRM* = salt-front location at high slack tide, in river miles, subscripts 100, 250, and 500 refer to chloride concentrations of 100, 250, and 500 milligrams per liter, respectively; and

SCWP = daily mean specific conductance at West Point, in microsiemens per centimeter at 25 degrees Celsius (µS/cm).

Equation	Coefficient of determination (r^2)	Standard error of estimate (Sxy) (miles)	Root mean square error (RMSE) (miles)	Specific conductance range (µS/cm)	Salt-front range (miles)
A	0.986	1.5	1.5	162 - 10,000	34.6 - 85.0
B	.994	1.0	.9	475 - 10,000	34.6 - 79.0
C	.992	1.1	1.2	1,100 - 10,000	35.5 - 72.0

Observed and predicted salt-front locations during some of the largest and highest tide-producing storms of this century are given in table 9. For example the storm of September 27, 1985, known as Hurricane Gloria, occurred at a river flow of 11,809 ft^3/s, which impeded the upstream movement of the salt front such that the chloride concentration at Chelsea Pump Station (RM 66.2) was less than 40 mg/L, and the computed location for the 100-mg/L salt front was RM 64.5. This computation provided a useful check on the accuracy of the relation, as did the winter storms of February 1985 and December 11, 1992 (table 9). Even though the maximum tide of December 11, 1992, was 3 ft higher than that of February 12, 1985, the flow on December 11 was 3 times that of the February storm. The largest high tide of this century occurred during the Great New England Hurricane of 1938, but freshwater inflow on the Hudson River was so large, estimated to be 200,000 ft^3/s at West Point (Paulsen and others, 1940), that the salt front was probably pushed seaward of the Battery (RM 0).

A chloride concentration of 342 mg/L was measured at the Poughkeepsie Water-Treatment Plant at RM 77.2 on November 20, 1964, during the severe drought of 1960-68. The drought-recurrence interval ranged from 35 to 80 years (Gravlee and others, 1991). Applying the regression equation from table 6 that relates chloride concentration upstream of West Point to specific conductance at West Point indicates that, on that day, the specific conductance at West Point would have been 10,780 µS/cm. Applying this value to the salt-front location equations in table 7 indicates the 100- and 250-mg/L chloride concentrations to be at RM 85.5 and 80.8, respectively. (Note: This use of the equation is for historical reference only and must be interpreted with caution because the specific-conductance value is beyond the range used to develop the equations.) This drought may have been the only time since Great Sacandaga Lake (fig. 1) was built in 1924 that the Natural Heritage Program's Kingston Deepwater site (fig. 2) actually contained the reported "dense saline" waters (New York State, 1990, p. 127-128). Applying the 5-day mean inflow (*flow* term) of 2,920 ft^3/s upstream from West Point and the 5-day tide level (*tidemax* term) of about 3.0 ft above mean sea level at West Point, as approximated from water levels recorded at the Battery by the National Ocean Service of the National Oceanic and Atmospheric Administration (written commun., 1993) to equation 4 yielded a 100-mg/L chloride concentration at RM 88.3, which is 2.8 mi upstream

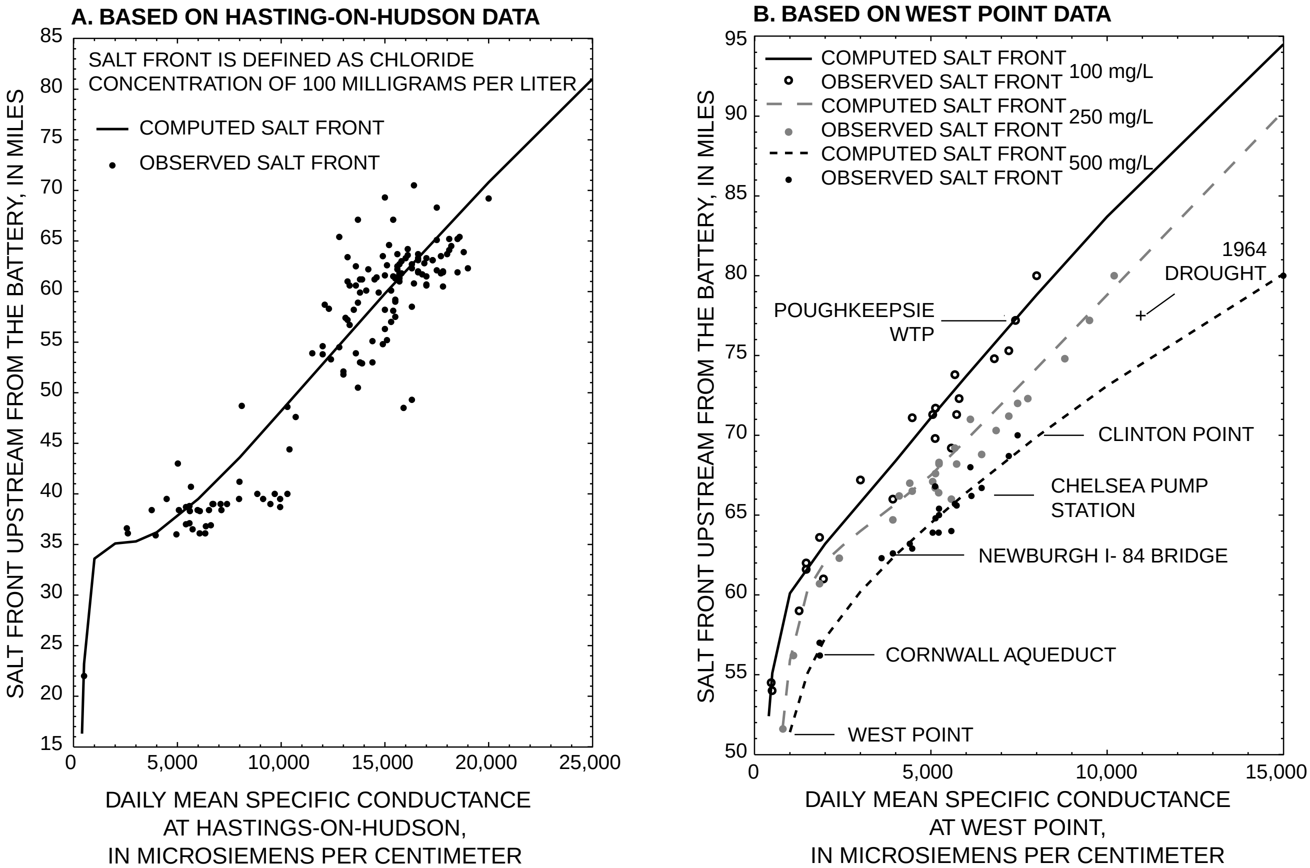


Figure 6. *Computed and observed relation between salt-front location and daily mean specific conductance in Hudson River, N.Y.: (A) 100-milligrams per liter salt-front location based on specific conductance values at Hastings-on-Hudson. (B) 100-, 250-, and 500-milligrams per liter salt-front locations based on specific conductance values at West Point.*

from the location computed from the 100-mg/L West Point specific conductance equation (table 7, eq. A).

Although empirical equations based on specific conductance and physical conditions at West Point are accurate predictors of salt-front locations, they cannot simulate the effect of hypothetical stresses such as low flows or increased withdrawals for water supply on the salt-front location; therefore, deterministic dynamic-wave hydraulic and solute-transport models were used for those purposes in this study.

Flow Simulation by One-dimensional Flow Model (BRANCH)

The USGS one-dimensional Branch-Network Dynamic Flow model (BRANCH) was used to simulate flow in the Hudson River under a wide range of inflow, tidal, and meteorological conditions. The tidal Hudson River is 153.7 mi long, and thalweg depth ranges from 15 ft just north of Albany (RM 152) to more than 225 ft near West Point-North Dock (RM 52.9, fig. 2). River width ranges from 600 ft just north of Albany to 18,000 ft in the bay near Haverstraw (fig. 3). Channel geometry in the estuary was represented in the models as a sequence of subreaches, each of which was divided into branches that are connected at nodal points and each branch was divided into segments, mainly on the basis of channel geometry. Each segment boundary is assigned cross-sectional data in the model. The reach between Green Island and Hastings-on-Hudson contains a total of 26 branches with 27 nodal points (fig. 3). Five additional branches were added to represent side-channel and tributary-storage areas as described by Stedfast (1982). The nodal point locations, distance downstream from Green Island, and number of cross sections in each branch are listed in table 10.

Table 8. *Observed and computed Hudson River salt-front locations, based on (1) combined inflow from Hudson River at Green Island and from five tributaries, and (2) tide elevations at West Point, N.Y.*

[ft^3/s, cubic feet per second]

Tributary Inflow[a] (ft^3/s)	Tide[b] (feet above sea level)	Salt-front Location		
		Observed[c]	Computed[c]	Error[d] (miles)
5,749	2.65	67.2	66.9	-0.3
15,351	2.82	54.0	49.1	-4.9
7,045	2.82	61.6	63.9	+2.3
17,537	2.66	54.5	45.9	-8.6
4,097	3.00	75.3	78.7	+3.4
4,768	2.51	73.8	69.9	-3.9
8,355	2.67	71.3	59.1	-12.2
4,458	2.46	69.8	70.9	+1.1
4,058	2.73	71.7	76.2	+4.5
4,062	2.78	71.1	76.7	+5.6
4,960	2.38	69.2	67.6	-1.6
7,343	2.66	71.3	61.7	-10.6
8,723	2.73	63.6	58.7	-4.9
5,765	2.87	66.0	68.9	+2.9
7,707	2.47	61.0	59.0	-2.0
13,716	3.67	59.0	56.4	-2.6
13,419	2.96	62.0	52.3	-9.7

[a] Mean 5-day prior inflow upstream from West Point.
[b] Mean maximum 5-day prior high tide at West Point.
[c] In river miles upstream from the Battery in New York City.
[d] Difference between observed and computed values.

Calibration and Verification

Model calibration entailed adjusting the coefficients of variables that affect flow in the river until the resulting simulated flow was similar to the measured flow. The final calibration for the entire 133-mi reach represents the values that gave the best overall fit (for weighted daily-mean bias from successive ebb- and flood-flow volumes and tidal-wave timing) in simulating net flow generated from tidal-cycle data collected at 11 discharge-measurement and 8 stage-measurement locations. Instantaneous errors may differ noticeably from observed discharge and stage values and exceed the reported weighted daily-mean bias and absolute error. Model verification entailed comparison of simulated flows with independent data sets (not used during calibration) that had been collected under differing tide and flow conditions.

Channel Geometry

Channel-geometry data were obtained from Stedfast (1980) and the National Ocean Service of the National Oceanic and Atmospheric Administration (the latter in the form of digital files and older hydrographic survey sheets); physical measurements of the river channel also were made. The Channel Geometry Analysis Program (CGAP) (Regan and Schaffranek, 1985) aided in the analysis, interpretation, and quantification of the physical properties of the channel. Segment division criteria were chosen that aid in the accuracy, convergence, and stability of the model (Schaffraneck and others, 1981). Segment divisions were chosen at locations where thalweg depth, averaged over 1 mi, changed by more than 30 ft. Additional segment divisions were chosen where cross-sectional area, averaged over 1 mi,

Table 9. *Salt-front locations in Hudson River, N.Y., during severe storms of the 20th Century*

[Locations shown in fig. 2. RM, river mile above The Battery, New York City; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

Date	Discharge† (cubic feet per second)	Maximum tide elevation (feet above mean sea level)	Salt-front location (RM)
9-21-38	200,000‡	8.2 ‡	0.0 ‡
2-12-85	6,500	3.78	73.5 [a] 73.1 [b]
9-27-85	11,809	4.58	64.5 [a]
12-11-92	20,800	6.75	61.7 [a] 60.3 [c]

† 5-day mean inflow for Hudson River at Green Island and 5 tributaries.

‡ Estimated.

[a] Computed from regression equation relating salt-front location to flow and maximum tide (eq.4).

[b] A known chloride concentration of 800 mg/L at RM 64.7 would yield a mean specific conductance of 6,000 µS/cm at West Point; therefore, the estimated location of the 100-mg/L salt front was at RM 73.1.

[c] A mean specific conductance of 1,060 µS/cm measured at West Point would place the 100-mg/L salt front at RM 60.3. The measured chloride concentration at RM 64.7 on December 11, 1992, was 37 mg/L.

Table 10. *Nodal-point and corresponding BRANCH data used in flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.*

[Locations are shown in figs. 2 and 3]

	Station Data			BRANCH Data		
Nodal point	*Number*[1]	*Name*	*Distance along thalweg downstream from Green Island (ft)*[2]	*Number*[3]	*Length (ft)*	*Number of cross sections*[4]
1	01358000	Green Island (Federal Dam)	0	--	--	--
2	01359139	Albany	45,024	1	45,024	6
3	--	Castleton-on-Hudson	88,304	2	43,280	4
4	--	Schodack Landing	130,544	3	42,240	4
5	--	Stockport	173,314	4	42,770	3
6	01361450	Catskill	218,714	5	45,400	4
7	01362187	West Camp	259,374	6	40,660	3
8	--	Saugerties	274,154	7	14,780	2
9	01364832	Turkey Point	295,274	8	21,120	--
10	01364840	Red Hook	300,554	9	5,280	--
11	--	Kingston	314,284	10	13,730	--
12	01372009	Rhinecliff	331,184	11	16,900	5
13	0137200910	Sturgeon Point	352,304	12	21,120	--
14	0137204020	Rogers Point (Hyde Park)	376,594	13	24,290	5
15	01372055	Poughkeepsie	415,144	14	38,550	4
16	01372059	Clinton Point (New Hamburg)	444,714	15	29,570	3
17	--	Chelsea	466,362	16	21,648	4
18	01372575	Beacon (Newburgh)	492,233	17	25,871	3
19	--	Pollepel Island	511,848	18	19,615	3
20	--	Breakneck Point (Catskill aqueduct)	518,712	19	6,864	2
21	--	Cold Spring	530,845	20	12,133	3
22	01374019	West Point	542,988	21	12,143	6
23	0137402390	Beverly Dock	550,932	22	7,944	--
24	01374320	Indian Point	596,844	23	45,912	6
25	0137448530	Bowline Point (Haverstraw)	620,604	24	23,760	4
26	01374486	Tellers Point	636,972	25	16,368	3
27	01376303	Hastings-on-Hudson[5]	701,916	26	64,944	7

[1] Numbers shown wherever data were collected.

[2] Distances from Stedfast (1980, 1982)

[3] Total number of branches was 26, with 27 nodal points. Refer to figure 3 and appendix I and II for details.

[4] Total number of mainstem cross sections was 84; an additional 10 cross sections represent storage.

[5] Hastings-on-Hudson is 21.5 miles upstream from the Batttery in New York City.

changed by more than 800 ft^2. A total of 84 cross sections were used to represent the geometry of the main stem of the tidal Hudson, and another 10 represent side-channel storage areas (Stedfast, 1982).

The channel-geometry characteristics of the study area are depicted in figure 3 as profiles at selected segment divisions; channel cross-sectional area and width at various stages for each segment are given in appendix I. A schematic diagram of the modeled river system is included in figure 3; the one-dimensional representation contains five subreaches—Green Island to Turkey Point, Turkey Point to Clinton Point, Clinton Point to West Point, West Point to Bowline Point, and Bowline Point to Hastings-on-Hudson.

Boundary Conditions

The BRANCH flow model is driven either by upstream and downstream flow, by stage, or by both, and by tributary inflow and wind velocity. In this study, Green Island flow was input as the upstream boundary condition, and stage at either Hastings-on-Hudson or Bowline Point was used as the downstream boundary condition. Stage data also were collected at Albany, Turkey Point, Rogers Point, Clinton Point, and West Point (fig. 1); these measured interim stages and their corresponding flows were used to calibrate and verify the model. The stage data were used to calculate starting water-surface elevations at all 27 nodal points. Inflows of tributaries were measured at Moordener Kill at Castleton-on-Hudson (01359750), Esopus Creek at Mt. Marion (01364500), Rondout Creek at Rosendale (01367500), Wallkill River at Gardiner (01371500), Wappinger Creek at Wappinger Falls (01372500), and Croton River at Croton Dam (01375000) (fig. 1). The drainage areas and flows for these gages were used to estimate flows for ungaged drainage areas between the gages and their respective tributary mouths (table 11). Wind-velocity and direction data were provided at Albany and LaGuardia Airports by NWS. Wind data rarely differed greatly between the two measurement sites, but when the wind was downstream (southward), Albany data were used, and when it was upstream (northward), LaGuardia data were used. An example of boundary input data is given in appendix II.

Table 11. *Nodal-point and corresponding boundary conditions used in Hudson River, N.Y., BRANCH flow model*

[Locations are shown in figs. 1, 2, and 3. mi^2, square miles]

Nodal point	Station number	Boundary condition and location*	Drainage area above gage site (mi^2)	Drainage area above mouth (mi^2)
1	01358000	Streamflow at Hudson River at Green Island	8,090	8,090
2	--	Wind direction and velocity at Albany	--	--
3	--	Storage near Castleton-on-Hudson	--	--
3	01359750	Streamflow at Moordener Kill at Castleton-on-Hudson	32.6	33
5	--	Storage near Schodack Landing	--	--
7	--	Storage near Stockport	--	--
9	--	Storage near Catskill	--	--
11	--	Storage near West Camp	--	--
13	01364500	Streamflow at Esopus Creek at Mt. Marion	419	425
	01367500	Streamflow at Rondout Creek at Rosendale	383	--
	01371500	Streamflow at Wallkill River at Gardiner	695	--
14	01372000	Streamflow for combined Rondout/Wallkill	1,078	1,172
18	01372500	Streamflow at Wappinger Creek near Wappinger Falls	181	210
26	01375000	Streamflow at Croton River at Croton Dam	378	381
27	01376303	Wind direction and velocity at Hastings-on-Hudson (LaGuardia Airport data)	--	--

* Location of lower boundary-condition stage data used for each model reach is given in tables 15 and 16.

Theta and Chi

Two factors that affect the magnitude and timing of the flow in the BRANCH model are *theta*, the finite-difference weighting factor for the spatial derivatives, and *chi*, a weighting factor for function values in the flow equations; both can range from 0.5 to 1.0. Several combinations were tested and a *theta* value of 1.0 and a *chi* value of 0.5 were selected; these values affected mainly the timing of flow.

Bed Friction and Internal Friction

Another important factor in model calibration is the flow-resistance coefficient, *eta*, which retards flow. Although principally dependent on channel roughness, the flow-resistance coefficient also may account for schematization inaccuracies and departures from assumed conditions (Schaffranek and others, 1981). The flow-resistance coefficients that were used in this study for the reach between Albany and Clinton Point were those previously calculated by Stedfast (1982). When the simulation represented only the reach between Green Island and West Point, the closest match for flow and stage resulted from a flow-resistance coefficient of 0.017 between Clinton Point and West Point. The computed and observed stages at Clinton Point for September 26-27, 1989 are plotted in figure 7. Similarly, measured flow at Tellers Point on August 22-23, 1990, was checked against flow data for the reach from the Bowline Point to Hastings-on-Hudson (fig. 8H); a flow-resistance coefficient of 0.0185 gave the best fit for this reach. Flow-resistance coefficients for model subreaches are listed in appendix II.

The reach from West Point (river width about 2,100 ft) south to Bowline Point (river width about 15,000 ft) is prone to variable-density stratification. These density dynamics cause large internal friction that can affect both the volume and timing of flows. The effect of density differences among reaches was investigated; the relation of water density to reach location when average discharge at Green Island ranged from 5,500 to 11,500 ft^3/s during the summers of 1989 and 1990 are plotted in figure 9. Because BRANCH algorithms assume constant density and one-dimensional flow, the simplification of the actual internal friction processes as incorporated in the model requires adjustments to the flow-resistance coefficient (*eta*) to correctly simulate observed flows. The flow-resistance coefficients for the reach between West Point and Bowline Point, where the river widens considerably, were optimized for those measurements to give the best fit. The flow-resistance factors are plotted in relation to specific conductance at Bowline Point in figure 10; model sensitivity analyses are summarized in table 12. The improvement resulting from the use of varied water-density coefficients between segments is minimal when compared to the constant-freshwater-density results and supports the theory that well-mixed reaches, no matter how varied the longitudinal density differences, will not greatly alter the tidal flow. Increasing the flow-resistance coefficient (*eta*) for the reach from West Point to Bowline Point to account for internal friction losses in conjunction with increased salinity gave an improvement of 17 percent for the August 1989 measurement. The final flow-resistance coefficients used for the reach between West Point and Bowline Point for all measurements made between June 1989 and August 1990 are given in table 13 and ranged from 0.0110 for a specific conductance at or below 1400 μS/cm to 0.040 for a specific conductance of about 9,000 μS/cm at Bowline Point.

The BRANCH model also requires that a momentum coefficient be defined that describes the horizontal and vertical velocity profiles. In this study, a value of 1.000 was used for computational purposes. In natural channels, momentum coefficient can be much greater than 1.000, but any resulting error in the

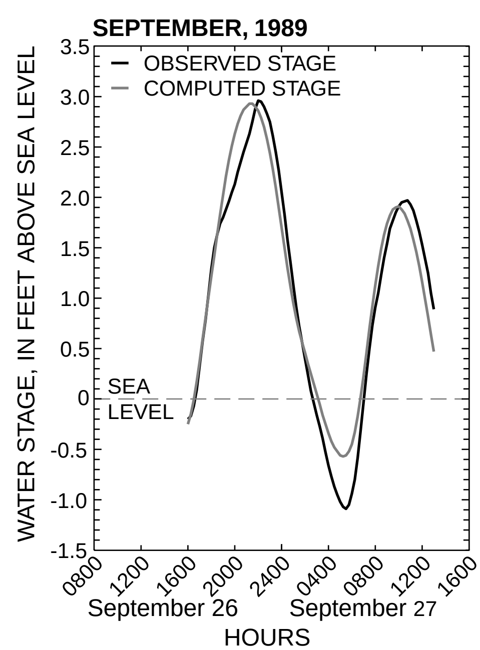


Figure 7. *Observed and computed stage of Hudson River at Clinton Point, N.Y., September 26-27, 1989.*

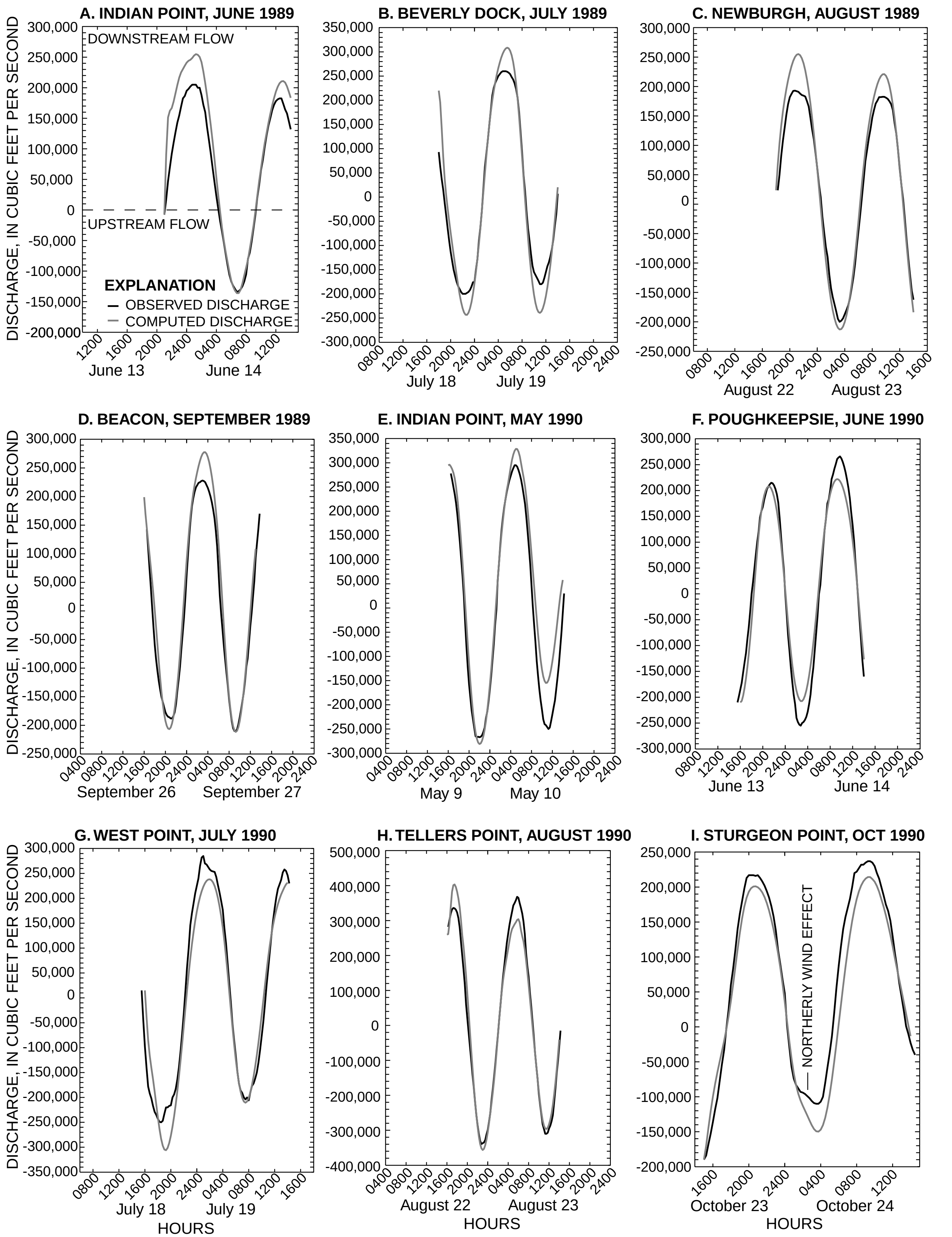


Figure 8. *Observed and computed discharge of Hudson River, N.Y., at nine sites in spring and summer of 1989 and 1990.*

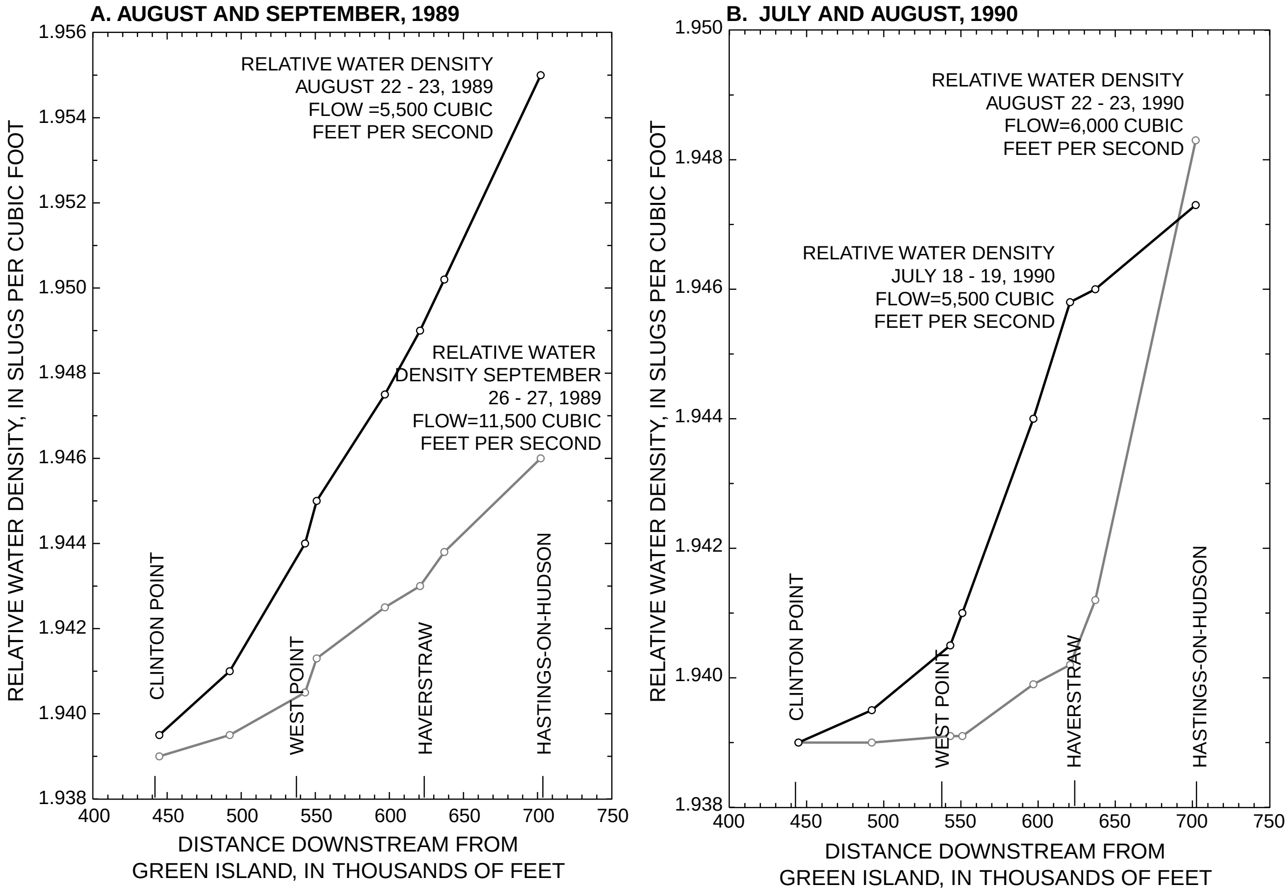


Figure 9. *Water density as a function of location at selected Green Island flows in 6.6-mile reach between Clinton Point and Hastings-on-Hudson, N.Y.: A. August and September 1989. B. July and August 1990.*

computation is assumed to be minimal because the importance lies in the relative difference between cross sections, rather than their actual magnitudes.

Wind Velocity

Wind-velocity data collected at Albany and LaGuardia Airports by the National Weather Service were input on a 3-hour frequency to provide 8 values per day. The average wind speeds at Albany and LaGuardia Airports during calendar year 1990 were 10.5 and 13.8 mi/h, respectively; wind speed during the flow measurements on August 22-23, 1989, was 8.8 mi/h at Albany and 11.2 mi/h at LaGuardia— similar to the annual 1990 values. A sensitivity test of wind effect was made for the August 1989 flow measurement at Newburgh, in which net velocity was increased by 3 mi/h and 6 mi/h. Results (table 14) indicate that increases in the 3- to 6-mi/h range do not cause greater than 10-percent bias in ebb- and flood-flow volume; therefore, wind data from either airport could have been used in the modeling without any significant change in results. A storm on October 24, 1990, at about 1 a.m. in the area of the flow measurement at Sturgeon Point (RM 90.4) was accompanied by wind from the north that impeded upstream flow; the wind velocity was reported to have exceeded 20 mi/h, and river-surface waves were 2 to 3 ft high. These high waves could have decreased the accuracy of flow measurements between 1 a.m. and 8 a.m. that day, and the need for increased flexibility in wind-data requirements for the modeling was noted. Because only one wind-velocity site (Albany) was represented in the model, and because the data represent only 3-hour intervals, the decrease in the upstream flow was difficult to replicate (fig. 8I). Shorter wind-data-collection intervals and use of additional wind-data sites would be useful in future modeling efforts because the study reach is too long to be accurately represented by only one wind-data site. To address this shortcoming, the lower end of the reach was moved 30.1 mi north, from Hastings-on-Hudson to West Point for the October 1990 simulation, to shorten

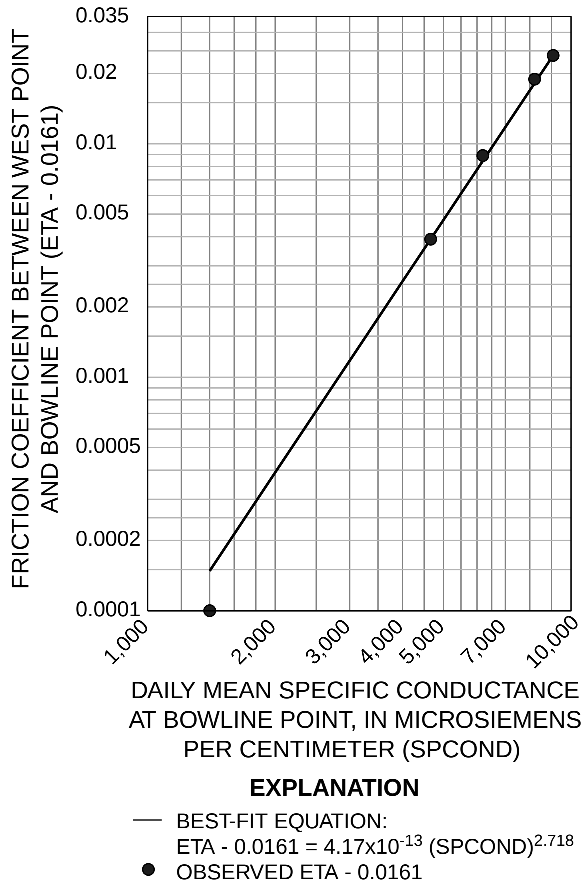


Figure 10. *Friction coefficient in relation to specific-conductance of Hudson River at Bowline Point for 17.8-mile reach from West Point to Bowline Point, N.Y.*

the reach and make the lower boundary-condition stages more representative of any wind-induced conditions at Sturgeon Point. This decreased the daily-mean absolute errors by 0.1 and 3.6 percent for October 23 and 24, 1990, respectively (table 16).

Results

The model for the reach between Green Island and Clinton Point was calibrated from 10 discharge measurements made at five locations (Poughkeepsie, Rhinecliff, Red Hook, Catskill, and Albany) during 1965-67 (Giese and Barr, 1967; Busby and Darmer, 1970) and 1979-80 (Stedfast, 1982). Model coefficients from the USGS modeling study of the Albany-to-Clinton Point reach (Stedfast, 1982) were used as the basis for this calibration. A recalculation done for this study incorporated tributary inflow and wind data and extended the reach 8 mi upstream from Albany to the Federal Dam at Troy so that Green Island flow could be used in place of Albany stage as the upstream boundary condition; flow-resistance coefficients (given in appendix II) were not changed, nor were previous datum corrections. The discharge and stage errors for the sites in this reach are given in table 15. Flow simulations for the 10 measurements of discharge used for model calibration had daily-mean biases that ranged from -21.0 to +4.8 percent; average flow-simulation bias was -6.6 percent (11.5 percent mean absolute error). Stage simulations had daily-mean biases from -0.03 to +0.22 ft (+0.07 mean bias; 0.16 ft RMSE); stage bias in 10 of 14 daily simulations ranged from 0 to +0.08 ft.

The model results for flows between Green Island and Clinton Point were verified with two sets of flow measurements made at Poughkeepsie (RM 76.5) during June 1990 and Sturgeon Point (RM 90.4) during October 1990. The discharge and stage errors for these two sites are given in table 16. Flow simulations for the two tidal-cycle measurements of discharge used for model verification had daily-mean biases that ranged from -13.9 to +15.0 percent; average flow-simulation bias was -1.5 percent (21.4 percent mean absolute error); stage simulations had daily-mean biases from -0.07 to +0.28 ft (+0.1 ft mean bias; 0.2 ft RMSE).

The model reach from Clinton Point to Hastings-on-Hudson was calibrated from three sets of flow and stage data collected at two sites in June and September of 1989 and May of 1990. The calibration for this reach used data from Indian Point and Beacon. The discharge and stage errors for these two sites are given in table 16. Flow simulations for the three measurements of discharge used for model calibration had daily-mean biases that ranged from -7.3 to +11.6 percent (the June 13, 1989, value was not used because of the short period represented, less than 3 hours); average flow-simulation bias was +4.9 percent (16.6 percent mean absolute error). Stage simulations had daily-mean biases from -0.05 to +0.08 ft (0 ft mean bias; 0.1 ft RMSE).

This model reach (Clinton Point to Hastings-on-Hudson) was verified with flow and stage data collected at four sites in July and August 1989 and July and August 1990. The discharge and stage errors for the verification measurements made at these sites—Beverly Dock (RM 50.1), West Point (RM 51.6), Newburgh (RM 61.4), and Tellers Point (RM 33.9)—are included in table 16. Simulations of flow at the times of the four discharge measurements used for

Table 12. *Effect of varying flow-resistance coefficients for Hudson River reach between West Point and Bowline Point, N.Y., on error in flow computations, and effect of varying water density for the reach between Clinton Point and Hastings-on-Hudson*

[Locations are shown in fig. 1]

Flow-resistance coefficient and density combinations	*Daily-mean bias in flow computation (percent)*		*Net bias in flow computation (percent)*
A. AUGUST 22-23, 1989	Aug. 22 (8 hours)	Aug. 23 (13.50 hours)	
Friction coefficient = 0.020 Density = 1.9390 at all cross sections	+33.9	+21.1	+25.8
Average density ranges from 1.939 at Clinton Point to 1.9550 at Hastings-on-Hudson	+28.7	+23.5	+25.4
Friction coefficient = 0.040 Density = 1.9390 at all cross sections	+21.7	+4.2	+10.7
Average density ranges from 1.939 at Clinton Point to 1.9550 at Hastings-on-Hudson	+17.8	+6.6	+10.8
B. SEPTEMBER 26-27, 1989	Sept. 26 (6 hours)	Sept. 27 (13 hours)	
Friction coefficient = 0.020 Density = 1.9390 at all cross sections	-8.5	+13.0	+6.2
Average density ranges from 1.939 at Clinton Point to 1.946 at Hastings-on-Hudson	+3.7	+13.1	+10.1
C. JULY 18-19, 1990	July 18 (8 hours)	July 19 (14 hours)	
Friction coefficient = 0.035 Density = 1.9390 at all cross sections	-13.7	-8.6	-10.5
Average density ranges from 1.939 at Clinton Point to 1.9473 at Hastings-on-Hudson	-11.2	-11.7	-11.5

model verification had daily-mean biases from -11.5 to +23.7 percent; average flow-simulation bias was +1.5 percent (10.7 percent mean absolute error). Stage simulations had daily-mean biases from -0.31 to +0.40 ft (+0.1 ft mean bias; 0.4 ft RMSE).

In summary, the model was calibrated and verified to a total of 19 tidal-cycle discharge measurements made at 11 locations with conventional and acoustic Doppler current-profiler methods. Maximum measured instantaneous tidal flow ranged from 20,000 ft^3/s at Albany to 368,000 ft^3/s at Tellers Point; daily-mean flow at Green Island ranged from 3,030 ft^3/s to 45,000 ft^3/s. Successive ebb- and floodflow volumes were measured and compared with computed volumes; daily-mean bias was -1.6 percent (range from -21.0 to +23.7 percent; 13.5 percent mean absolute error). Daily-mean deviation between simulated and measured stage at 8 locations (from Bowline Point to Albany) over the 19 tidal-cycle measurements averaged +0.06 ft (range from -0.31 to +0.40 ft; 0.21 ft RMSE). These results indicate that the model can accurately simulate flow in the Hudson River under a wide range of inflow, tidal, and meteorological conditions. Examples of the match between observed and computed flow data at nine selected sites in 1989 and 1990 are plotted in figure 8; stage data on September 26-27 at Clinton Point are plotted in figure 7.

Table 13. *Specific conductance of Hudson River at Hastings-on-Hudson and Bowline Point, and flow-resistance coefficient (eta) for West Point to Bowline Point, N.Y. in 1989-90 flow simulations*

[Locations are shown in fig. 2. Dash indicates no data]

Date (1989-90)	Specific conductance, in microsiemens per centimeter at 25˚Celsius						Flow-resistance coefficient (eta)
	Hastings-on-Hudson		Bowline Point				
	Daily mean	Mean	Top daily mean	Middle daily mean	Bottom daily mean	Mean	
1989							
June 13	3,820	4,380	536	1,770	1,550	1,530	0.0155
June 14	4,940		777	2,370	2,170		
July 18	13,700	14,700	8,590	9,950	11,940	10,140	.0400
July 19	15,700		9,660	9,520	11,200		
Aug. 22	17,500	17,700	7,590	7,990	8,890	8,030	.0400
Aug. 23	17,900		7,450	7,760	8,480		
Sept. 26	8,400	7,945	4,840	5,510	5,320	4,660	.0200
Sept. 27	7,490		3,770	4,300	4,190		
1990							
May 9	--	--	1,890	2,310	2,660	1,980	.0155
May 10	--		1,540	1,620	1,830		
June 13	--	--	4,320	6,400	7,460	6,190	.0250
June 14	--		4,600	6,720	7,660		
July 18	--	--	7,790	8,020	8,760	8,210	.0350
July 19	--		7,890	8,100	8,700		
Aug. 22	10,700	10,600	1,530	2,180	1,720	1,980	.0155
Aug. 23	10,500		1,700	2,610	2,110		
Oct. 23	8,620	7,650	1,240	1,760	1,810	1,400	.0110
Oct. 24	6,680		759	1,340	1,480		

Table 14. *Bias in simulated successive ebb- and flood-flow volumes of Hudson River at Newburgh, N.Y., August 22-23, 1989, resulting from simulated increase in wind velocity*

[All values are percent error]

		Wind-velocity increase, in miles per hour		
Date	*Time*	*0**	*3*	*6*
Aug. 22	1800 - 2400	+21.8	+26.0	+31.6
Aug. 23	0015 - 0530	-1.1	-5.0	-9.7
	0545 - 1330	+10.7	+12.4	+14.2
	1345 - 1400	-2.3	-4.4	-4.6
Weighted mean error		+10.8	+11.7	+12.9

* See figure 8C

SALT-FRONT MOVEMENT SIMULATION BY THE BRANCH-NETWORK FLOW MODEL

Conservative particle (tagged solutes) movement between Green Island and Hastings-on-Hudson during the 26 days from July 18 through August 13, 1990, was examined before the transport-modeling effort began, and ten particle-entry locations were used to plot the traveltimes of conservative particles. The movement of ten different particles for the 26-day period is plotted in figure 11A. For example, the average flow at Green Island during July 18-29 was 5,970 ft^3/s; from then until August 5 it averaged 4,220 ft^3/s, and during August 6-13 it averaged 12,000 ft^3/s. A particle entering at Bowline Point moved about 6 mi in the first 18 days (0.33 mi/d during July 18-August 4), then, when the average flow increased to 12,000 ft^3/s, the particle moved 11 mi in the next 8 days (1.38 mi/d). Average particle speeds downstream from Green Island are plotted in figure 11B as a function of discharge. These are the maximum rates at which a conservative particle would move; nonconservative (reactive) particles would tend to move more slowly. The net increases in the distance a particle moves downstream for flow increases of 1,000 ft^3/s, 3,000 ft^3/s, and 5,000 ft^3/s at Green Island are plotted in figure 11C.

Simulated Effect of Withdrawals and Flow Increases

Hypothetical withdrawals at selected points were simulated, and the resulting salt-front positions were calculated, in an effort to quantify the upstream movement of the salt front that would result from withdrawals to provide emergency supplies for New York City.

Withdrawals at Kingston, Chelsea, and Newburgh

The Chelsea Pump Station at present is capable of withdrawing 100 Mgal/d from the Hudson River, but withdrawals of as much as 300 Mgal/d have been discussed. Therefore, five scenarios of withdrawals totaling 300 Mgal/d were simulated with the BRANCH model: (1) 300 Mgal/d at Chelsea or Newburgh, (2) 100 Mgal/d at Chelsea and 200 Mgal/d at either Kingston or Newburgh, and (3) 100 Mgal/d at Kingston and 200 Mgal/d at Newburgh; the effect of these withdrawals on upstream movement of a conservative particle started at selected locations is summarized in table 17A. Results for conservative particles injected between Green Island and Tellers Point indicate that, of the five scenarios evaluated for the period of moderate flow (July 18 to August 13, 1990), the scenario that would have the smallest effect on salt-front movement is the one in which the Chelsea Pump Station withdrawal would increase from 100 Mgal/d to 300 Mgal/d. For this simulation, discharge at Green Island averaged 7,100 ft^3/s, and the initial salt-front location was at Clinton Point or below. The withdrawal that would have the smallest effect in the reach from Poughkeepsie upstream to Turkey Point would be withdrawal of 300 Mgal/d at Newburgh. The scenarios that would have the greatest effects on salt-front movement include withdrawals at Kingston, where the greater withdrawal could move a front initially near Poughkeepsie upstream by 1.1 mi.

Increased Rates of Withdrawals at Newburgh

Withdrawals of 1,000 ft^3/s (646 Mgal/d), 3,000 ft^3/s (1,939 Mgal/d), and 5,000 ft^3/s (3,232 Mgal/d) at Newburgh during the 26-day period between July 18 and August 13, 1990 were simulated; the effect of these withdrawals after 26 days on the movement of conservative particles that started at selected locations is shown in table 17B. Flows at Green Island from July 18 through August 5 averaged 5,000 ft^3/s; only during

Table 15. *Calibration error for discharge and stage measured at five locations on Hudson River between Green Island and Clinton Point, N.Y., before 1981*

[Locations are shown in fig. 2. All simulations represent reach from Green Island to Clinton Point unless otherwise noted. Bias, daily-mean bias; RMSE, root mean square error; horseman, hours and minutes; --, dash indicates no record]

		Calibration error					
		Discharge			Stage		
Date of measurement	Location	Bias (percent)	Absolute error (percent)	Error weight (hours:min)	Bias (feet)	RMSE (feet)	Error weight (hours:min)
Aug. 11, 1965	Poughkeepsie	-20.9[1]	20.9[1]	7:30	+0.01	0.26	9:00
May 24, 1966	Poughkeepsie	-6.6	22.8	16:00	+.01	.04	16:00
May 25, 1966	Poughkeepsie	-6.2	6.2	10:45	+.02	.04	11:00
May 24, 1966	Bard Rock (Hyde Park)	--	--	--	-.01	.07	16:00
May 25, 1966	Bard Rock (Hyde Park)	--	--	--	+.04	.08	11:00
Aug. 30, 1966	Poughkeepsie	+4.8	20.1	9:18	+.05	.06	9:15
Aug. 30, 1966	Bard Rock (Hyde Park)	--	--	--	+.08	.11	14:00
Aug. 30, 1966	Albany	--	--	--	-.03	.24	14:00
June 21, 1967	Poughkeepsie	-9.9	9.9	10:24	+.16	.16	16:00
June 22, 1967	Poughkeepsie	-8.1	8.1	8:36	+.12	.12	11:00
June 21, 1967	Rhinecliff	-2.5	2.8	11:23	+.19	.22	16:00
June 22, 1967	Rhinecliff	--	--	--	+.07	.12	11:00
Aug. 21, 1979	Poughkeepsie	-7.2	7.2	11:08	--	--	--
Aug. 21, 1979	Red Hook	-0.2	4.6	9:18	--	--	--
Aug. 21, 1979	Albany	-21.0	21.0	7:50	+.22	.47	13:00
Aug. 21, 1979	West Camp	--	--	--	0	.20	13:00
Mar. 26, 1980	Albany	-6.1	6.1	10:45	--	--	--
Apr. 18, 1980	Catskill	+4.7[2]	4.7[2]	4:45	--	--	--
Weighted mean error		-6.6	11.5		+.07	.16	

[1] Wind velocity used for this measurement was recorded at LaGuardia Airport; wind velocity recorded at Albany Airport for all others.

[2] Green Island to West Camp reach.

the last 7 days of the period (August 7-13) did flows exceed 10,000 ft^3/s. Withdrawals of 1,000 ft^3/s, 3,000 ft^3/s, and 5,000 ft^3/s at Newburgh would shorten the downstream movement of a particle (salt front) started at the Chelsea Pump Station (RM 66.2) (table 17B) by 1.4 mi, 4.6 mi, and 7.4 mi, respectively; flows north of Rogers Point (RM 81.0) would be unaffected. This indicates that these withdrawals would affect at least 21 mi of the river upstream of Newburgh; the 5,000-ft^3/s withdrawal also would affect as much as 27 mi of the river downstream from Newburgh, and the 1,000- and 3,000-ft^3/s withdrawals would affect the river for at least 9 mi downstream from Newburgh.

Increased Flow at Green Island

Flow increases of 1,000 ft^3/s, 3,000 ft^3/s, and 5,000 ft^3/s at Green Island for the period from July 18 through August 13, 1990, were used to simulate the effects of flow augmentations on conservative-particle movement; results are included in table 17B and figure 11C. Generally, all other conditions remaining constant, an increase in discharge at Green Island would increase the rate of downstream movement of a particle. Given an initial average Green Island flow of 7,100 ft^3/s a flow increase of 1,000 ft^3/s could cause a particle started at the Chelsea Pump Station to move 1.4 mi farther downstream than it would otherwise.

Table 16. *Calibration and verification error for discharge and stage measured at seven locations on Hudson River, between Green Island and Hastings-on-Hudson, N.Y., after 1981*

[Locations are shown in fig. 2. All simulations represent reach from Green Island to Hastings-on-Hudson unless otherwise noted. Calib, calibration; Verif, verification; Bias, daily-mean bias; RMSE, root mean square error; hours:min, hours and minutes]

			Calibration or verification error					
			Discharge			Stage at West Point		
Date of measurement	Location	Calib. (C) or verif. (V)	Bias (percent)	Absolute error (percent)	Error weight (hours:min)	Bias (feet)	RMSE (feet)	Error weight (hours:min)
June 13, 1989	Indian Point	C	+53.8[1]	53.8[1]	2:56	+0.05[1]	0.28[1]	3:00
June 14 1989	Indian Point	C	+5.0[1]	9.7[1]	9:44	+.03[1]	.06[1]	14:00
July 18, 1989	Beverly Dock	V	+23.7	23.7	5:07	+.21[2]	.64[2]	8:00
July 19, 1989	Beverly Dock	V	-0.7	3.4	12:33	-.13[2]	.52[2]	14:00
Aug. 22, 1989	Newburgh	V	+21.3	21.3	5:45	+.17	.63	9:00
Aug. 23, 1989	Newburgh	V	+4.7	5.5	13:25	+.06	.28	14:00
Sept. 26, 1989	Beacon	C	-6.1	6.1	7:30	+.06[3]	.13[3]	8:00
Sept. 27, 1989	Beacon	C	+11.6	16.6	12:45	+.08[3]	.08[3]	13:00
May 9, 1990	Indian Point	C	+6.9[3]	6.9[3]	4:54	+.05[3]	.07[3]	7:30
May 10, 1990	Indian Point	C	-7.3[3]	23.4[3]	12:45	-.05[3]	.08[3]	14:00
June 13, 1990	Poughkeepsie	V	+15.0	26.4	8:00	+.28	.34	8:00
June 14, 1990	Poughkeepsie	V	-13.9	13.9	8:00	+.06	.20	14:00
July 18, 1990	West Point	V	-11.5	11.5	8:00	-.31	.37	8:00
July 19, 1990	West Point	V	-8.6	8.6	13:45	+.11	.23	14:00
Aug. 22, 1990	Tellers Point	V	+18.9	18.9	7:45	+.40[4]	.50[4]	8:00
Aug. 23, 1990	Tellers Point	V	-9.9	9.9	11:52	0[4]	.19[4]	14:00
Oct. 23, 1990	Sturgeon Point	V	-12.1[5], -12.2[6]	12.1[5], 12.2[6]	6:29	-.07[3]	.17[3]	9:00
Oct. 24, 1990	Sturgeon Point	V	+1.2[5], +3.7[6]	27.3[5], 30.9[6]	13:44	+.06[3]	.09[3]	14:00
Weighted mean error			+1.9	14.9		+.05	.25	

[1] Albany to Bowline Point reach.

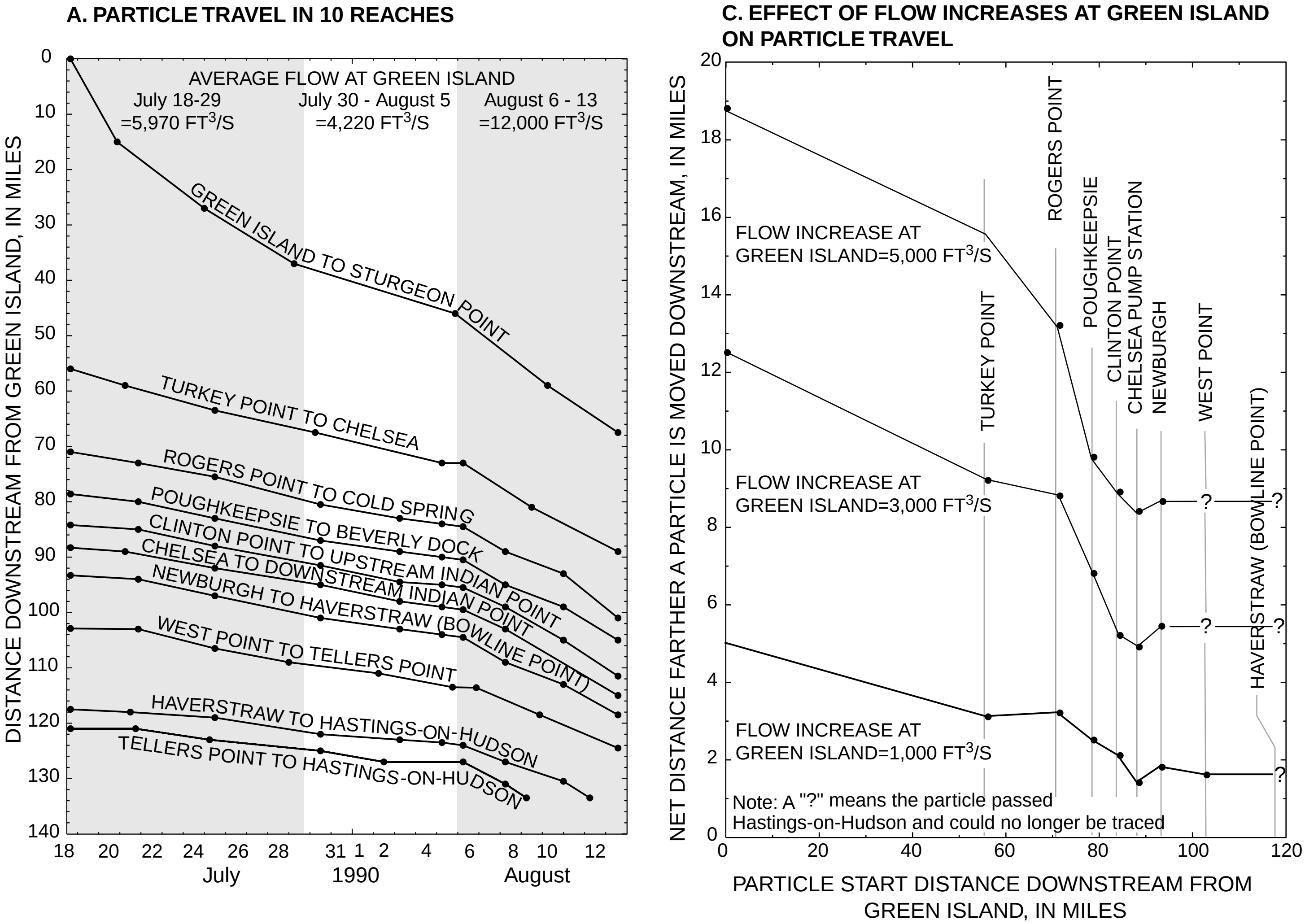
[2] Stage at Clinton Point.

[3] Green Island to Bowline Point reach.

[4] Stage at Bowline Point.

[5] Green Island to West Point reach; high winds noted.

[6] Green Island to Hastings-on-Hudson reach; high winds noted.



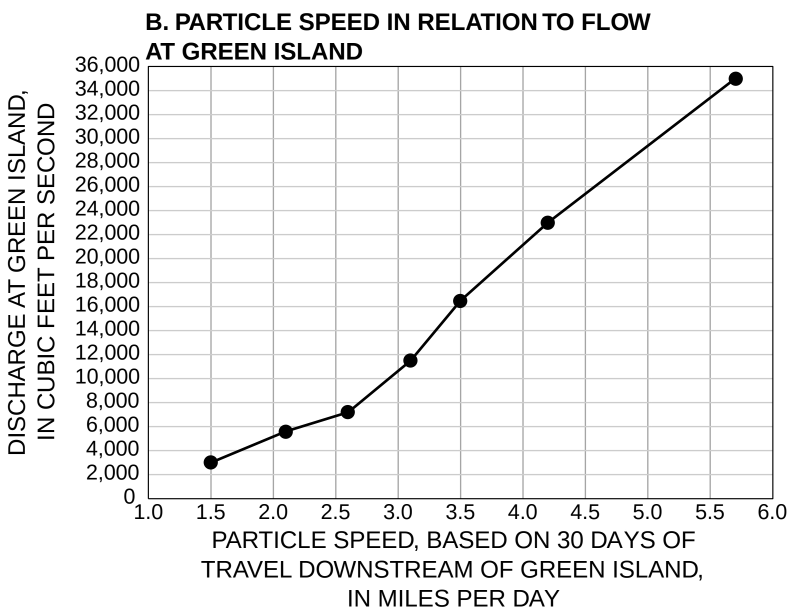


Figure 11. *Travel of a conservative particle in the Hudson River downstream of Green Island, July 18 through August 13, 1990: A. Travel in 10 reaches during three different flows. B. Particle speed in relation to discharge at Green Island. C. Effect of three increases in flow at Green Island on particle travel. (Refer to table 17B).*

Table 17. *Effect of simulated withdrawals from Hudson River, and augmented inflow at Green Island, N.Y., on conservative particle movement 26 days after entry, July 18 through August 13, 1990*

[Locations are shown in fig. 2. Values to right of shaded column indicate change in particle location, in miles, from the corresponding location in shaded column (unstressed-condition location). Negative values represent upstream movement; positive values indicate downstream movement. Values in shaded column are in river miles below Green Island dam. --, indicates change could not be determined because particle left model reach; ft^3/s, cubic feet per second]

A. With simulated withdrawals, in million gallons per day, at Chelsea, Newburgh, and Kingston for an average discharge of 7,100 ft^3/s at Green Island

Particle-entry point			*Particle distance below Green Island dam after 26 days, in miles (zero withdrawal)*	*Chelsea withdrawal*		*Newburgh withdrawal*		*Combined withdrawals*		
Station number	*Station location and river miles below Green Island*			*100*	*300*	*100*	*300*	*Chelsea (100) + Newburgh (200)* 300	*Chelsea (100) + Kingston (200)* 300	*Kingston (100) + Newburgh (200)* 300
01358000	Green Island	0	66.6	0	0	0	**0**	0	-0.2	-0.1
01364832	Turkey Point	55.9	90.6	-.3	-.1	0	**0**	-.2	-1.2	-.6
0137204020	Rogers Point	71.3	102.8	-.4	-1.0	-.1	**-.3**	-.6	**-1.4**	-.9
01372055	Poughkeepsie	78.6	109.5	-.2	-.6	-.1	**-.3**	-.4	**-1.1**	-.7
01372059	Clinton Point	84.2	113.6	-.2	**-.5**	-.2	-.6	-.5	-1.0	-.8
--	Chelsea	88.3	116.6	-.1	**-.4**	-.2	-.6	-.5	-.7	-.7
01372575	Newburgh-Beacon	93.2	119.2	-.1	**-.3**	-.2	-.7	-.6	-.6	-.7
01374019	West Point	102.8	125.1	-.1	**-.4**	-.3	-.8	-.7	-.7	-.8
0137448530	Bowline Point	117.5	133.0[1]	--	--	--	--	--	--	--
01374486	Tellers Point	120.6	133.0[1]	--	--	--	--	--	--	--

B. With increased rates of withdrawal at Newburgh or flow augmentation at Green Island

Particle-entry point			*Particle distance below Green Island dam after 26 days, in miles (zero withdrawal)*	*Withdrawals at Newburgh (million gallons per day)*			*Augmentation at Green Island (cubic feet per second)*		
Station number	*Station location and river miles below Green Island*			*646*	*1,939*	*3,232*	*1,000*	*3,000*	*5,000*
01358000	Green Island	0	66.6	0	0	0	5.0	12.5	18.8
01364832	Turkey Point	55.9	90.6	0	0	0	3.1	9.2	15.6
0137204020	Rogers Point	71.3	102.8	-.7	-1.3	-2.0	3.2	8.8	13.2
01372055	Poughkeepsie	78.6	109.5	-.7	-2.2	-3.7	2.5	6.8	9.8
01372059	Clinton Point	84.2	113.6	-1.2	-3.4	-5.8	2.1	5.2	8.9
--	Chelsea	88.3	116.6	-1.4	-4.6	-7.4	1.4	4.9	8.4
01372575	Newburgh-Beacon	93.2	119.2	-1.4	-4.8	-8.9	1.8	5.4	8.7
01374019	West Point	102.8	125.1	-1.7	-5.5	-8.5	1.6	--	--
0137448530	Bowline Point	117.5	133.0[1]	--	--	-7.0	--	--	--
01374486	Tellers Point	120.6	133.0[1]	--	--	-3.7	--	--	--

[1] The most downstream cross section in the flow model is Hastings-on-Hudson, 133.0 miles downstream from Green Island. A particle cannot be traced once it passes this location.

SALT-FRONT MOVEMENT SIMULATION BY THE BLTM SOLUTE-TRANSPORT MODEL

The Branched Lagrangian Solute-Transport Model (BLTM) was used to simulate the effects of hypothetical withdrawals on chloride concentrations in the reach from Turkey Point to Bowline Point. The BLTM differs from BRANCH particle tracking in that BRANCH accounts only for movement by advection (transport by currents) and does not account for solute movement by the combined effects of turbulent flow and molecular diffusion. The effects of molecular diffusion and turbulence are 1 to 2 orders of magnitude smaller than the effects of advection (Fischer and others, 1979) and are reflected in BLTM through the variable DQQ (the inverse of **dispersion**; thus, the lower the DQQ, the higher the rate of mixing).

Model Calibration

Daily discharge data were collected from May through August 1990 and during August 1991. Flows at each of the 84 cross sections between Green Island and Hastings-on-Hudson were computed at 15-min intervals, then transformed into daily values. Only the 61.0-mi reach from Turkey Point to Bowline Point was used in the model calibration. This reach was treated as a single branch in BLTM for the 1990 and 1991 data. Daily chloride concentrations at Bowline Point were used as the lower boundary condition to simulate daily values for West Point, where several periods of measured daily chloride data were available for calibration.

In 1990, the salt front did not move much farther upstream than Newburgh; therefore, calibration could not be made for locations north of Newburgh. In 1991, the salt front moved much farther upstream, however, and the calibration reach for this period was extended to the Poughkeepsie Water-Treatment Plant. West Point had the only operating chloride-concentration gage in August 1991, so the reach used for the 1991 calibration was Turkey Point to West Point.

The solute-transport model uses a variable DQQ, which was assigned to each cross section to control the rate of mixing in the model. Because upstream tributary inflow can have a large effect on DQQ, periods of high flow (April through June) and periods of low flow (July through August) were evaluated separately.

Turkey Point to Bowline Point

The 61.0-mi reach from Turkey Point to Bowline Point included 36 cross sections.

Boundary Conditions

Boundary conditions for the 1990 simulations were (1) daily chloride concentration at Bowline Point and Turkey Point, (2) daily flow at each cross section, and (3) the area and width of each cross section as computed by the flow model.

Initial Conditions

DQQ values were assigned to each cross section on the basis of cross-sectional width and data on the upstream movement of the salt front from Newburgh in 1990. Starting flows were generated by the flow model. Initial chloride concentrations were derived from measured Bowline Point and West Point data and from relations between chloride concentrations at these sections and those measured at other cross sections during salt-front delineations.

Results

The BLTM was used to simulate chloride transport in the 61-mi reach from Turkey Point (RM 98.5) to Bowline Point (RM 37.5) under two seasonal conditions in 1990—spring conditions of high inflow and low salinity (April-June; daily-mean discharge at Green Island 23,700 ft^3/s) and summer conditions of low inflow and high salinity (July-August; daily-mean discharge at Green Island 7,150 ft^3/s). Measured chloride concentrations at Bowline Point were used to drive the BLTM simulations, and concentrations measured at West Point were used for calibration. Observed and simulated chloride concentrations for the April-June 1990 calibrations and the July-August 1990 calibrations for West Point are plotted in figure 12. Mean bias in simulated chloride concentration for the April-June 1990 data (fig. 12A, observed range 12 to 201 mg/L; 30 mg/L RMSE) was –16 mg/L. Mean bias for the July-August 1990 data (fig. 12B, observed range 31 to 2,000 mg/L; 535 mg/L RMSE) was +126 mg/L. The August 1-29 calibration (fig. 12C) had a mean bias of 11 mg/L. Even though frictional resistance between West Point and Bowline Point varies considerably, depending on tributary-inflow conditions, a single mean value of the flow-resistance coefficient (*eta*) was used by the flow

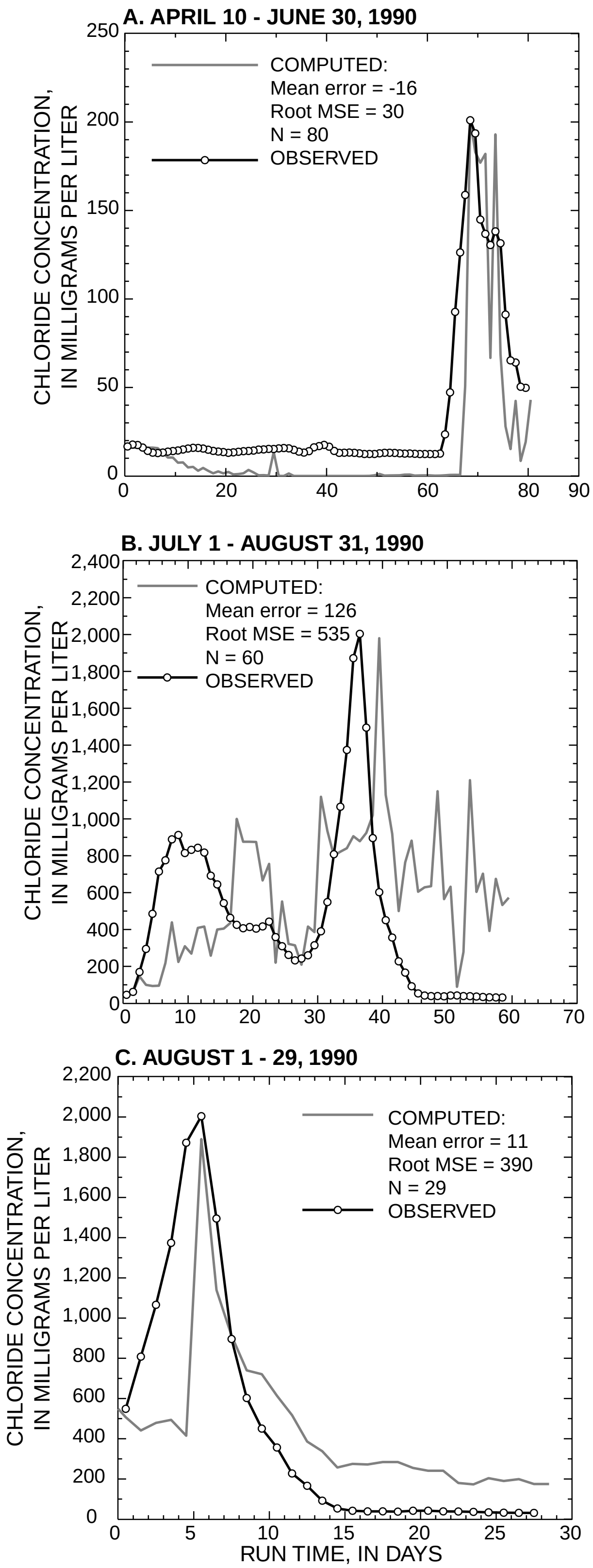


Figure 12. *Observed and simulated chloride concentrations at West Point, N.Y., as a function of time during three solute-transport model calibrations in 1990: A. April 10-June 30. B. July 1-August 31. C. August 1-29.*

model in this reach for the entire simulation period; this could account for the high simulated chloride concentrations after the August peak, when flows at Green Island more than tripled. Relating the flow-resistance coefficient for this reach to specific conductance values at Bowline Point on a continuous basis could improve the accuracy of simulations.

Turkey Point to West Point

The reach between Turkey Point and West Point was calibrated to the August 1991 data to obtain DQQ values for these 26 cross sections. No continuous specific conductance data were collected in the reach above West Point during August 1991 (the only period during the study in which the salt front moved north of the bay at Newburgh); therefore, the accuracy of the solute-transport model at several locations was checked by comparison with salt-front-delineation data that related specific conductance at West Point to chloride concentration at West Point, Catskill Aqueduct (RM 56.2), Newburgh, Chelsea Pump Station, and Clinton Point. The regression equations are shown in table 6; the computed 1991 chloride concentrations at Chelsea Pump Station and Clinton Point used for calibration are given in table 5. These equations also were used to calculate the daily chloride concentration at the IBM pier below Poughkeepsie (RM 72.3), the Central Hudson Powerplant just south of the Mid-Hudson Bridge at Poughkeepsie (RM 74.8), and the Poughkeepsie Water-Treatment Plant (RM 77.2).

Boundary Conditions

The West Point daily chloride concentrations were used to simulate input data for chloride concentration at Chelsea Pump Station and Clinton Point. Other input categories for each cross section were (1) daily flow computed by the BRANCH flow model, (2) cross-section area, and (3) cross-section width.

Initial Conditions

The DQQ values used for the reach downstream of Newburgh for July and August 1990 also were used for the August 1991 calibration. Values of DQQ were adjusted for the reach from Turkey Point downstream to Newburgh; the data are included in table 18. Initial chloride concentrations were obtained in the same manner as the 1990 calibrations.

Table 18. *Observed and simulated chloride concentrations in Hudson River between Turkey Point and West Point, N.Y., August 9-31, 1991*

[Locations are shown in fig. 2. mi, miles. Concentrations are in milligrams per liter]

Station name	Distance below Green Island (mi)	Dispersion coefficient (DQQ) from BLTM model	Chloride concentration	
			Observed maximum instantaneous	Simulated maximum daily
Turkey Point	55.92	0.5	--	--
Rhinecliff	62.72	.5	--	--
Bard Rock	71.32	.5	--	25
Rogers Point	73.52	.5	--	27
St. Andrews on the Hudson	75.63	.5	--	35
Poughkeepsie Water Treatment Plant	77.33	--	48	43
Poughkeepsie railroad bridge	78.13	--	60	71
Poughkeepsie	78.63	1.0	--	75
Central Hudson Powerplant	79.73	--	115	--
Milton	81.23	1.0	--	141
IBM pier	82.23	--	204	194
Clinton Point	84.23	.1	464	264
Marlboro	85.53	7.0	--	363
Cedar Cliff	86.83	.1	--	400
Chelsea Pumping Station	88.33	4.0	990	629
Brockway	90.93	3.8	--	--
Newburgh, I-84 Bridge	92.23	--	1,440	945
Newburgh-Beacon	93.23	3.3	--	1,070
Hammond	95.43	2.5	--	--
Pollepel Island	96.94	.1	--	--
Catskill Aqueduct/Breakneck Point	98.24	.1	2,450	1,630
Little Stony Point	99.44	.1	--	--
--	100.04	6.0	--	--
--	100.84	8.0	--	--
West Point North Dock	101.51	10.0	--	--
Gees Point	101.87	12.0	--	--
--	102.29	20.5	--	--
West Point South Dock	102.86	--	3,150	2,260

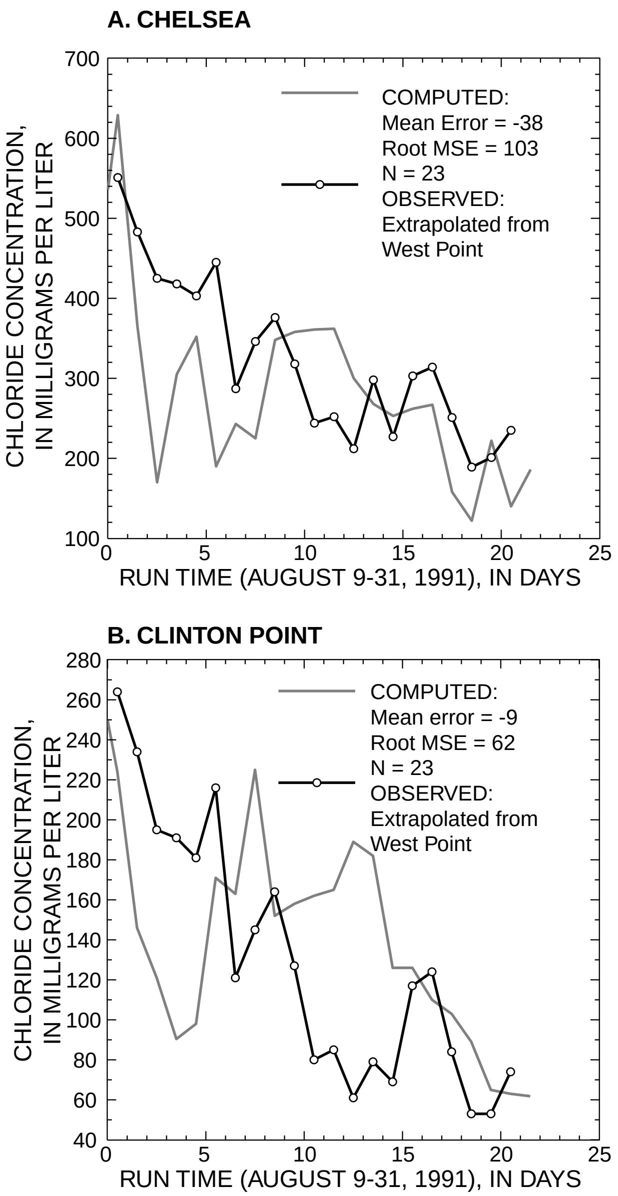


Figure 13. *Observed and simulated chloride concentrations during solute-transport-model calibration, August 9-31, 1991: A. At Chelsea. B. At Clinton Point.*

Results

Simulated chloride concentrations at Chelsea Pump Station and Clinton Point are shown in figure 13A and 13B, respectively. For reference, the measured maximum instantaneous chloride concentrations at many sites are shown in table 18 along with the maximum daily concentrations simulated by the solute-transport model. The main purpose of the August 1991 calibration was to establish reasonable DQQ values for the reach from Newburgh to Poughkeepsie for subsequent withdrawal simulations. Mean biases in BLTM-simulated daily mean chloride concentrations for August 1991 of -38 mg/L at Chelsea Pump Station (range from 189 to 551 mg/L; 103 mg/L RMSE) and -9 mg/L at Clinton Point (range from 53 to 264 mg/L; 62 mg/L RMSE) were similar to those obtained for West Point for July and August 1990 simulations. The combined DQQ values for the reaches above and below West Point, which represent a dispersion ranging from 35 to 250 m^2/d (average 140 m^2/d), were then used in the simulations of (1) withdrawals at Chelsea, Newburgh, Hyde Park, and (2) flow augmentation at Green Island.

Effects of Withdrawals and Flow Augmentations on Salt-front Location

The major objective of this study was to simulate the effects of hypothetical withdrawals and flow augmentation on the salt-front location. Withdrawal simulations for Chelsea or Newburgh were based on April-August 1990 data, and withdrawal simulations for Hyde Park were based on August 1991 data, as were the simulations of increased flow at Green Island. The 1990 data were based on measurements at Bowline Point, whereas the 1991 data were based on measurements at West Point; thus, the simulated salt-front locations are only relative. Effects of simulated withdrawals on the flow field and chloride distribution may propagate out to (and then converge at) the site used as the model boundary, beyond which the upstream effects become limited by the unaffected (constant)-boundary-condition data. The simulated locations would be more accurate if the southern boundary of the reach were pure seawater because chloride concentrations lower than that of seawater at this boundary could result in lesser salt-front movement.

Withdrawals at Chelsea during High Flow

Withdrawals of 3,000 ft^3/s and 6,000 ft^3/s at Chelsea Pump Station were simulated from the April 1-June 30, 1990 data. Flows at Green Island during this period were relatively large, averaging 25,200 ft^3/s, and, therefore, provided ideal conditions for evaluating the effects of high-flow "skimming"—large withdrawals under relatively high freshwater flow conditions. Results (fig. 14A) indicate that a withdrawal of 1,939 Mgal/d (3,000 ft^3/s) would not measurably affect the local chloride concentration, but that withdrawing at twice that rate (3,878 Mgal/d or 6,000 ft^3/s) could increase it to 250 mg/L. A withdrawal rate of 3,000 ft^3/s could cause the 250-mg/L salt front to move 5 mi upstream from its unstressed-condition location at RM 49.7, and a withdrawal of 6,000 ft^3/s could cause it to move 16 mi upstream to a point close to the Chelsea Pump Station.

Withdrawals at Chelsea or Newburgh

Simulated withdrawals of 5,000 ft^3/s at Chelsea or Newburgh were based on data collected from July 1 through August 31, 1990, when flow at Green Island averaged 7,150 ft^3/s. A simulated withdrawal of 5,000 ft^3/s at Chelsea Pump Station caused the 250-mg/L salt front to move 10 mi upstream from its unstressed-condition location at RM 56.4, and the same rate of withdrawal at Newburgh caused it to move 3.5 mi upstream (fig.14B); the effect of both withdrawals became negligible at the Poughkeepsie Water-Treatment Plant. If withdrawals were increased, or, more likely, if flow at Green Island were to decrease, the salt front could move upstream beyond Poughkeepsie.

The effect of a 100-Mgal/d withdrawal is extrapolated from simulations of larger withdrawals because 100 Mgal/d (155 ft^3/s) represents less than one-half of 1 percent of the measured tidal flow volume (excursion) occurring in the lower Hudson River near Chelsea Pump Station. For example, the floodflow volume at a measured cross section at Newburgh on August 22, 1989, from 1733 to 2335 hours, totaled -2.809×10^9 ft^3 (incoming tide). A constant withdrawal of 155 ft^3/s in this 6-hour period would represent 3.3666×10^6 ft^3 of water, or 0.12 percent of the measured excursion. Note also that the flow model was calibrated to discharge measurements that carry an uncertainty at least of $\pm$5 percent. Running the model with the 100 Mgal/d withdrawal is possible but running the model with a series of larger withdrawals (which are computationally more significant than 100 Mgal/d) and extrapolating to the 100-Mgal/d withdrawal provides greater reliability.

The results of simulated withdrawals shown in figures 14A and 14B were combined as figure 14C to estimate the effects of a 100-Mgal/d withdrawal at the Chelsea Pump Station. The BLTM simulations were carried out for two different flows at Green Island that encompass the range of inflow conditions to which BLTM was calibrated. Overall, the continuous withdrawals based on July 1-August 31, 1990 data had a larger effect — Green Island flows during this period averaged 7,150 ft^3/s, and a simulated continuous withdrawal of 100 Mgal/d at Chelsea Pump Station resulted in an upstream salt-front movement of less than 0.1 mi. The same withdrawals based on April 1-June 30, 1990 data, during which Green Island flows were 3 times greater (averaged 25,200 ft^3/s) also resulted in an upstream movement of the salt front of less than 0.1 mi. The BLTM estimates are similar to the results in table 17A, which lists the effect of a continuous 100-Mgal/d withdrawal on the position of a conservative particle after 26 days (July 18-August 13, 1990), when Green Island flows averaged 7,100 ft^3/s. The 100-Mgal/d withdrawal at Chelsea Pump Station could move the particles about 0.1 mi upstream of the unstressed-condition location, given an initial salt-front location, at or downstream of Chelsea. Withdrawals of 300 Mgal/d from any combination of Chelsea or Newburgh could result in upstream movement of the salt front of as much as 1.0 mi, given an initial salt-front location between West Point and Rogers Point.

Withdrawals at Hyde Park

Simulated withdrawals of 2,500 ft^3/s and 5,000 ft^3/s at Hyde Park were based on the August 1991 chloride concentrations at West Point. The average flow for this period at Green Island was 4,700 ft^3/s; this added to a tributary inflow of 500 ft^3/s from the intervening drainage area, gives a flow of about 5,200 ft^3/s at West Point. Results (fig. 14D) indicate that, for withdrawals of 2,500 ft^3/s or 5,000 ft^3/s, the 250-mg/L salt front would move upstream 2.6 and 3.1 mi, respectively, from an unstressed-condition location at RM 69.7. Because Green Island flows were increasing after August 9, 1991, and tide height was decreasing after the monthly spring tide, earlier flows of less than 4,700 ft^3/s could have resulted in a greater upstream movement of the salt front.

Flow Augmentations at Green Island

Increased river flows at Green Island were simulated to evaluate the effect of flow augmentations on the salt-front location. Simulated low flows at Green Island were increased by 1,000 and 5,000 ft^3/s. The daily mean flow at Green Island during August 9-31, 1991, was 4,400 ft^3/s—about a 90-percent flow duration (flow that is exceeded 90 percent of the time), as indicated by 45 years of continuous

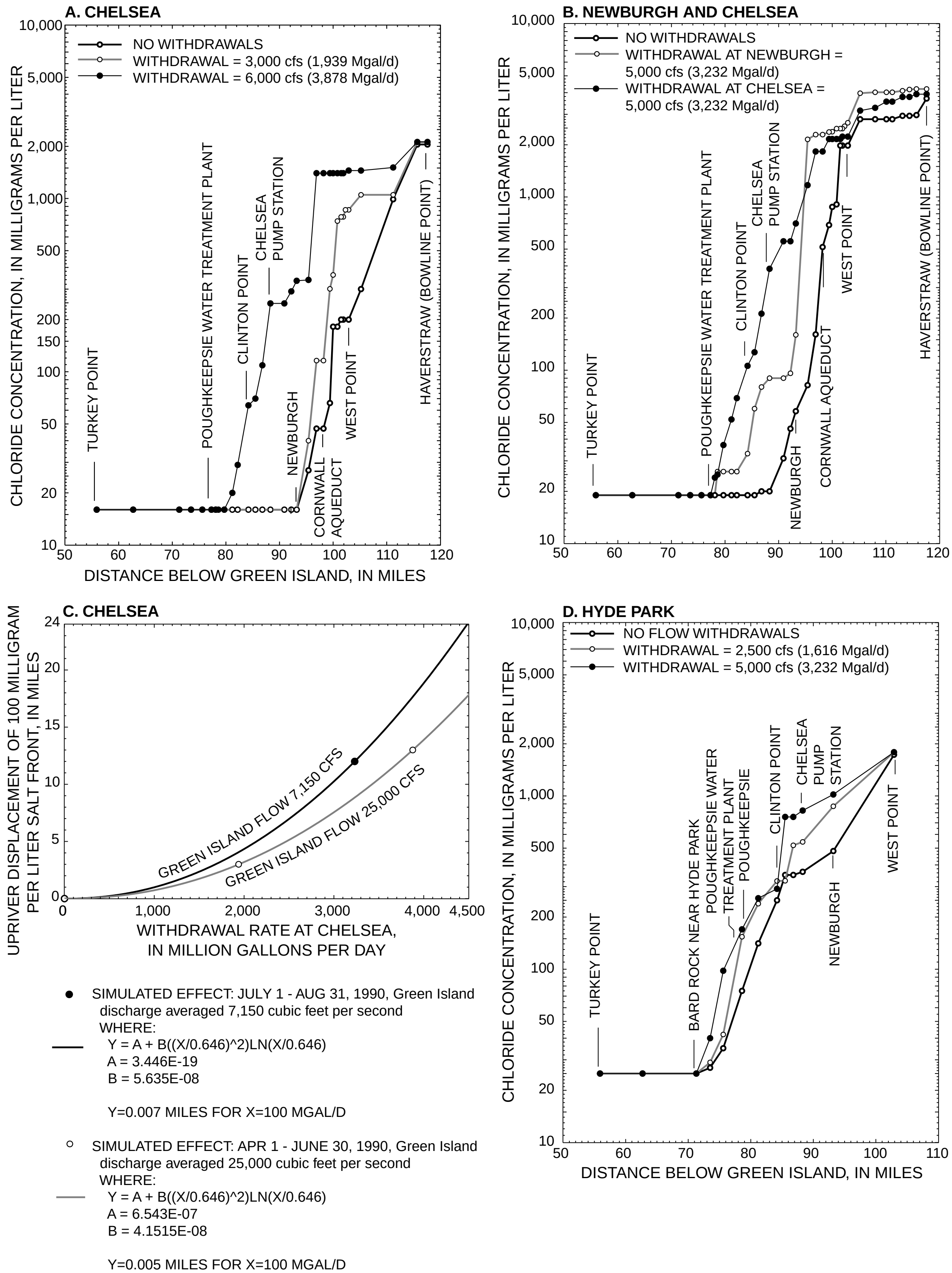


Figure 14. *Simulated chloride concentration of Hudson River, N.Y., at selected sites in reach from Turkey Point to Haverstraw, in relation to hypothetical water-withdrawals at: A. Chelsea, based on high-flow (April 1-June 30, 1990) data. B. Newburgh and Chelsea, based on low-flow (July 1-August 31, 1990) data. C. Combined results from (A) and (B) showing upriver movement of 100-mg/L chloride front as a function of withdrawals at Chelsea during high and low discharges (25,200 and 7,150 cubic feet per second at Green Island). D. Bard Rock near Hyde Park, based on low flow (August 9-31, 1991) discharges.*

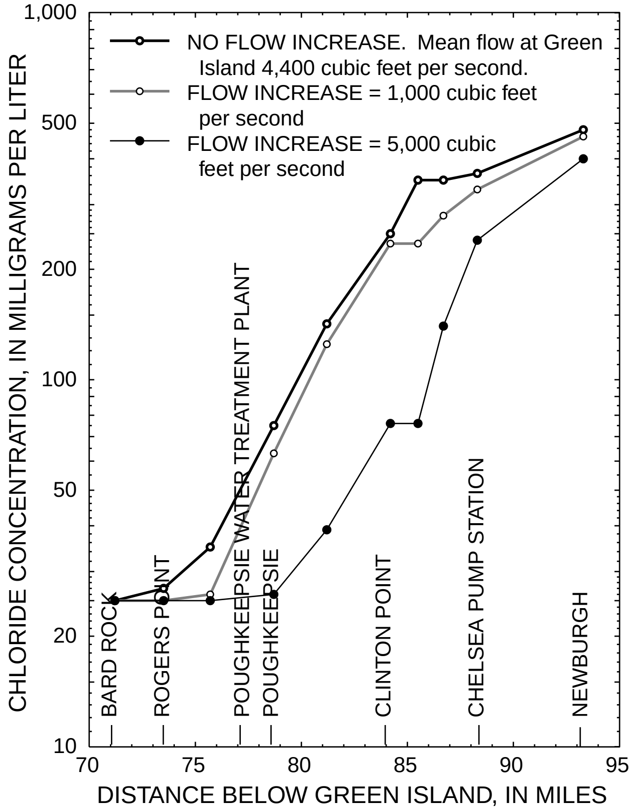


Figure 15. *Simulated chloride concentration of Hudson River, N.Y., at selected sites between Hyde Park and Newburgh, resulting from simulated 10-day flow increases of 1,000 and 5,000 cubic feet per second at Green Island, August 9-31, 1991.*

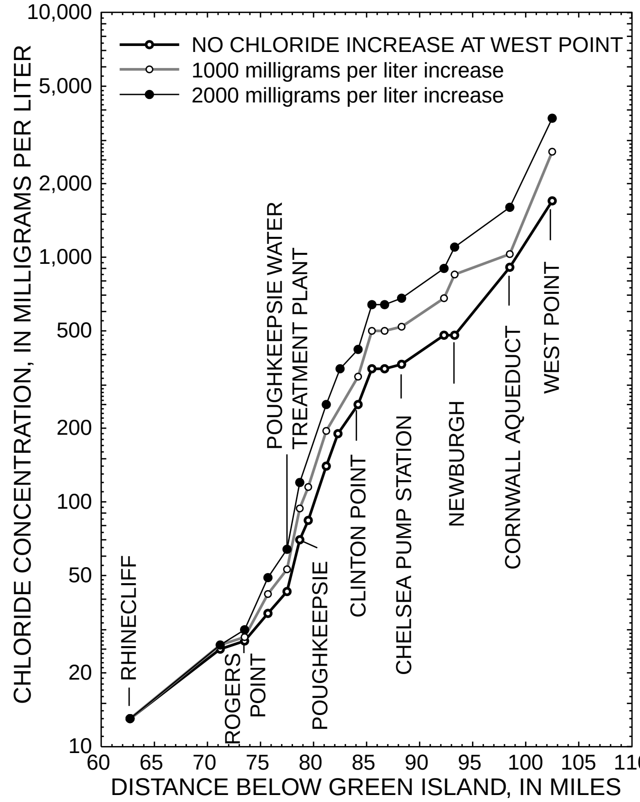


Figure 16. *Chloride concentration in Hudson River, N.Y., at selected sites between Rhinecliff and West Point resulting from simulated chloride increases of 1,000 and 2,000 milligrams per liter at West Point, August 9-31, 1991.*

records collected at Green Island. Results (fig. 15) indicate that an increase of 1,000 ft^3/s could cause the 100-mg/L salt front to move 0.6 mi downstream from its unstressed-condition location at RM 73.9; a 5,000-ft^3/s increase would move it 6.2 mi downstream.

Chloride Increases at West Point

The solute-transport model (BLTM), as previously discussed, is driven in part by the chloride concentration at the lower (southern) boundary. Ideally the chloride concentration at the lower boundary would be fairly constant (equivalent to ocean salinity, typically 18,000 to 20,000 mg/L), and the boundary would be far enough from withdrawal points that its chloride concentration would be unaffected by the withdrawals.

The reach used for simulation of increased chloride concentration during August 9-31, 1991, was the 46.9 mi reach from West Point (lower boundary) north to Turkey Point. Chloride concentrations at West Point were far less than 18,000 mg/L, and concentrations above 3,100 mg/L were rare. The simulated withdrawals at Newburgh caused some of the profiles of chloride concentration in relation to river mile to converge at West Point, indicating that the withdrawal would affect the concentrations at West Point. Because this type of withdrawal simulation cannot alter the lower-boundary data, lower boundary chloride concentrations were artificially increased at West Point to simulate the effect of increased lower-boundary salinity on the salt-front position north of West Point. The test concentrations were 1,000 and 2,000 mg/L greater than the measured chloride concentrations, and the results (fig. 16) indicate that a chloride increase of 1,000 mg/L could cause the 100-mg/L salt front to move 0.9 mi upstream from its unstressed-condition location at RM 73.9, and a 2,000 mg/L increase could move it 1.5 mi upstream. The effects of both increases in concentration becomes negligible just north of Rogers Point (RM 81.0).

SUMMARY AND CONCLUSIONS

New York City's water-supply system may be inadequate to meet the current demand during periods of drought. Use of the tidal part of the Hudson River is being explored as a supplemental source of water supply. One proposal entails withdrawal of Hudson River water from locations near Newburgh, Chelsea, or Kingston, but the extent to which this would cause the salt front to advance to points where it could adversely affect community water supplies is unknown. The U.S. Geological Survey (USGS), in cooperation with the New York City Department of Environmental Protection, New York State Department of Environmental Conservation, and the Hudson Valley Regional Council studied the effects of hypothetical water withdrawals on the movement of the salt front. To simulate effects of proposed withdrawals on salt-front location, the USGS, (1) compiled salt-front-related information from previous studies and public utilities along the lower Hudson River; (2) installed and operated tide-stage, discharge, and water-quality stations at key locations; (3) performed tidal-cycle discharge and salinity measurements under a wide range of hydrologic conditions; (4) used these data to calibrate and verify models to simulate the forces that affect flow and saltwater movement in the estuary; and (5) used the USGS one-dimensional Branch-Network Dynamic Flow model (BRANCH) in conjunction with the USGS one-dimensional Branched Lagrangian Solute-Transport Model (BLTM) to simulate the effect of several hypothetical water-withdrawals on the salt-front location.

Under normal seasonal tide and inflow conditions, the salt front and associated transition zone ranges from below Hastings-on-Hudson (RM 21.5) during high-flow periods in spring to New Hamburg (RM 67.7) during low-flow periods in late-summer, a distance of about 50 mi. Data collected for this study were used to derive regression equations to compute (1) chloride concentrations from measured specific conductance values, (2) chloride concentrations at Chelsea Pump Station and Clinton Point from specific-conductance values measured at West Point, (3) salt-front location from specific conductance values measured at West Point and Hastings-on-Hudson, and (4) salt-front location from tide levels at West Point and inflows at Green Island and five tributaries. Salt-front locations that were predicted from daily mean specific conductance at West Point had standard errors of estimate of 1.5 mi for the 100-mg/L front, 1.0 mi for the 250-mg/L front, and 1.1 mi for the 500-mg/L front. An empirical relation for the 100-mg/L salt-front location was also obtained by regression analysis in which chloride concentration was related to maximum tide stage at West Point and daily mean inflow from Green Island and five tributaries. The average bias was +2.4 mi. For historical reference, both methods were used to simulate the maximum upstream salt movement during (1) the 1964 drought and (2) three storms that produced some of the largest and highest tides of this century; results indicate that the salt front could have moved upstream as far as RM 85 on November 20, 1964, when the chloride concentration at Poughkeepsie was 342 mg/L. Although lunar tides are usually the main factor in salt-front movement on a daily basis, the extremely low 6-month average flow of 3,230 ft^3/s at Green Island during the 1964 drought allowed greater-than-normal upstream salt-front movement.

The Branch-Network Dynamic Flow model (BRANCH) was used to simulate flow in the Hudson River under a wide range of inflow, tidal, and meteorological conditions. A previous model of flow between Albany and Clinton Point near New Hamburg (Stedfast, 1982) was extended 8 mi upstream to Green Island and 49 mi downstream to Hastings-on-Hudson to encompass 133 mi of the lower Hudson River. Green Island flow was used in place of Albany stage as the upstream boundary. Calibration included tributary inflows and wind data in the model.

The reach upstream from Clinton Point has fairly uniform channel geometry and nonsaline water, whereas the reach downstream has nonuniform channel geometry and variable salinity, depending upon tidal movement. A variable flow-resistance coefficient for the 14.1-mi reach between West Point and Bowline Point at Haverstraw was used to adjust model results for the combination of abrupt changes in channel width—from 10,000 ft to 2,000 ft between Bowline Point at Haverstraw and West Point—and the effects of variable water density. These coefficients ranged from 0.0110 for a specific conductance of 1400 µS/cm or less at Bowline Point to 0.040 for a specific conductance of about 9,000 µS/cm.

The BRANCH flow model was calibrated and verified to 19 tidal-cycle discharge measurements made at 11 locations with conventional and acoustic Doppler current-profiler methods. Maximum measured instantaneous tidal flow ranged from 20,000 ft^3/s at

Albany to 368,000 ft^3/s at Tellers Point; Green Island daily-mean flow ranged from 3,030 ft^3/s to 45,000 ft^3/s during these tidal flow measurements. Successive ebb- and flood-flow volumes were measured and compared with computed volumes; daily-mean bias was -1.6 percent (range from -21.0 to +23.7 percent; 13.5 percent mean absolute error). Daily-mean deviation between simulated and measured stage at eight locations (from Bowline Point to Albany) over the 19 tidal-cycle measurements averaged +0.06 ft (range from -0.31 to +0.40 ft; 0.21 ft RMSE). These results indicate that the model can accurately simulate flow in the Hudson River under a wide range of flow, tidal, and meteorological conditions.

The effects of water density and wind velocity on flow were tested through a sensitivity analysis. Although the density term could be varied at each cross section, doing so gave only minimal improvement in flow error. The use of variable densities would have decreased the computational error if the channel geometry of reaches with high water density had been more uniform, but the irregular widening of these reaches allows greater lateral mixing than longitudinal mixing; thus, a **two- or three-dimensional** model would be needed to decrease the density-related error in simulated flow.

The Branched Lagrangian Solute-Transport Model (BLTM) was used to simulate chloride transport in the 61-mi reach from Turkey Point to Bowline Point under two seasonal conditions in 1990—one representing spring conditions of high inflow and low salinity (April-June), and the other representing typical summer conditions of low inflow and high salinity (July-August). Daily chloride oncentrations measured at Bowline Point were used to drive the BLTM simulations; measured daily chloride concentrations collected at West Point were used for calibration. Mean bias in simulated chloride concentration for the April-June 1990 data (observed range of 12 to 201 mg/L; 30 mg/L RMSE) was –16 mg/L. For the July-August 1990 data (observed range of 31 to 2,000 mg/L; 535 mg/L RMSE), the mean bias was +126 mg/L. The salt front or saltwater-freshwater interface on the Hudson River was defined as the furthest upstream location where the chloride concentration exceeded 100 mg/L. The chloride concentration at Clinton Point never exceeded 100 mg/L in 1990; therefore, solute transport between West Point and Poughkeepsie was evaluated from August 1991 data. The BLTM then was used to simulate chloride concentrations at Chelsea Pump Station and Clinton Point. Regression equations, based on daily mean values of specific conductance measured at West Point, were used to obtain daily mean chloride concentrations at Chelsea Pump Station and Clinton Point for model analysis. Mean biases in BLTM-simulated daily mean chloride concentrations for August 1991 were –38 mg/L at Chelsea Pump Station (range of 189 to 551 mg/L; 103 mg/L RMSE) and –9 mg/L at Clinton Point (range of 53 to 264 mg/L; 62 mg/L RMSE). The DQQ values (dispersion coefficient) for the reaches above and below West Point represent a range in dispersion from 35 to 250 m^2/d (average 140 m^2/d).

The BRANCH model was used to simulate various combinations of withdrawals at Kingston, Chelsea, and Newburgh to simulate their effect on the travel of a conservative particle. The Chelsea Pump Station at present is capable of withdrawing 100 Mgal/d from the Hudson River which could result in upstream particle movement of 0.1 mi. Withdrawals of (a) 300 Mgal/d at Chelsea or Newburgh, (b) 100 Mgal/d at Chelsea and 200 Mgal/d at either Kingston or Newburgh, and (c) 100 Mgal/d at Kingston and 200 Mgal/d at Newburgh, were simulated. Of the 300 Mgal/d scenarios evaluated, the one resulting in the smallest movement of the salt front in the reach below Poughkeepsie entailed increasing the Chelsea Pump Station withdrawal from 100 to 300 Mgal/d—resulting in a 0.5 mi upstream movement, and the scenario that would have the smallest effect in the reach from Poughkeepsie upstream to Turkey Point would be the withdrawal of 300 Mgal/d at Newburgh. Scenarios that included withdrawals at Kingston had the greatest effect on salt-front movement; a front starting near Poughkeepsie could move upstream by 1.1 to 1.4 mi.

Withdrawals of 3,000 ft^3/s (1,939 Mgal/d) and 6,000 ft^3/s (3,878 Mgal/d) at Chelsea Pump Station were simulated with the BLTM model and high-flow (April 1-June 30, 1990) data. Flows at Green Island during this period averaged 25,200 ft^3/s and, therefore, provided ideal conditions for evaluation of high-flow "skimming"—large withdrawals under relatively high freshwater flow conditions. A withdrawal of 3,000 ft^3/s could cause the 250-mg/L salt front to move 5 mi upstream from its unstressed (non-pumping) condition location at RM 49.7, and a withdrawal of 6,000 ft^3/s could cause it to move 16 mi upstream to a point close to the Chelsea Pump Station.

A BLTM-simulated withdrawal of 5,000 ft^3/s (3,232 Mgal/d) at Chelsea Pump Station during a low-flow period (July 1-August 31, 1990) when flow at Green Island averaged 7,150 ft^3/s, caused the 250-mg/L salt front to move 10 mi upstream from its unstressed-condition location at RM 56.4. The same withdrawal rate at Newburgh caused it to move 3.5 mi upstream; the effect of both withdrawals became negligible at the Poughkeepsie Water-Treatment Plant. If withdrawals were increased or, more likely, if flow at Green Island were to decrease, the salt front could move upstream beyond Poughkeepsie.

The effect of a 100-Mgal/d withdrawal rate at either Chelsea Pump Station or Newburgh was extrapolated from simulations of larger withdrawals because 100 Mgal/d (155 ft^3/s) represents less than one-half of 1 percent of the measured tidal flow volume occurring in the lower Hudson River near Chelsea Pump Station. For example, a constant withdrawal of 155 ft^3/s at a cross section at Newburgh on August 22, 1989, would represent only 0.12 percent of the measured floodflow volume. The flow model was calibrated to discharge measurements that carry an uncertainty at least of ±5 percent. Running the model with the 100-Mgal/d withdrawal is possible but running the model with a series of larger withdrawals (which are computationally more significant) and extrapolating to the 100-Mgal/d withdrawal provides greater reliability.

The effects of a 100-Mgal/d withdrawal at the Chelsea Pump Station were investigated through simulations for two different Green Island flow regimes that, together, encompass the range of inflow conditions to which BLTM was calibrated. Simulated continuous withdrawals of 100 Mgal/d at Chelsea Pump Station at low flow (July 1-August 31, 1990, when Green Island flows averaged 7,150 ft^3/s), resulted in an upstream movement of the salt front of less than 0.1 mi, as did the same withdrawals at high flow (April 1-June 30, 1990, when Green Island flows averaged 25,200 ft^3/s). The BLTM estimates closely match the conservative-particle-tracking results for the effect of a continuous withdrawal of 100-Mgal/d at Chelsea on the position of a conservative particle after 26 days during low-flow conditions (July 18-August 13, 1990, during which Green Island flows averaged 7,100 ft^3/s). The 100-Mgal/d withdrawal at Chelsea Pump Station could move the particles about 0.1 mi upstream of the unstressed-condition location, given an initial salt-front location at, or downstream from Chelsea. Withdrawals of 300 Mgal/d from any combination of Chelsea or Newburgh could result in upstream movement of the salt front of as much as 1.0 mi, given an initial salt-front location between West Point and Rogers Point.

In summary, the BRANCH model can be used to simulate flow in the Hudson River under a wide range of inflow, tidal, and meteorological conditions. The BLTM model can be used to estimate solute transport when only one representative mean concentration per cross section is required, and when the salt front is within the calibrated reach—in this case between Turkey Point and Bowline Point.

Future use of the models described in this report could be improved by altering the model to accommodate (1) variable water-density conditions through adjustment of the flow-resistance coefficient in all reaches, rather than just the reach between West Point and Bowline Point, (2) input of more than one source of wind-velocity data and at a greater frequency, and (3) selection of DQQ as a function of river flow and initial water density. Simulation of cross-sectional mixing for reaches with irregular widths could be improved by using two- or three-dimensional transport models.

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GLOSSARY

Terms that are set in **bold** within the text are discussed here. Other technical terms common to the field of computational hydraulics are discussed in Schaffranek (1989).

Continuity equation.—The continuity equation is based on Newton's first law (conservation of mass), which states that matter can neither be created or destroyed; this means that, assuming no change in storage, the rate at which a given mass is flowing into a given space (control volume) is equal to the rate at which the equivalent mass is flowing out. The continuity equation, in its simplest form, is written as

$$Q_1 = Q_2$$

or

$$A_1U_1 = A_2U_2$$

where

Q is discharge (flow rate), in units of volume per time;
A is cross-sectional area, in units of length squared;
U is velocity, in units of distance per time; and
subscripts *1* and *2* represent the upstream and downstream ends of the reach, respectively. Further discussion of the continuity equation and conservation of mass are given in Roberson and Crowe, 1980; Chow, 1959; Mahmood and Yevjevich, 1975; and most introductory texts on open-channel flow.

Datum.—A point, line or surface used as a reference, as in surveying, mapping, or geology (American Heritage Dictionary, 1982). Most USGS gages are referenced to a particular datum that is defined in each station description. All stage data in this report have been referenced to sea level (National Geodetic Vertical Datum of 1929 [NGVD of 1929]). See also "Hudson River Datums" and "NGVD of 1929".

Diffusion-wave model.—See "Flow conditions"

Dimensions.—Throughout this report, the three dimensions of the river are described as *longitudinal*, meaning length from upstream to downstream, *horizontal*, meaning width from side to side, and *vertical* meaning depth from surface to bottom. A one-dimensional system, as described herein, refers only to changes in the longitudinal direction. A two-dimensional system can be either vertically averaged and can describe longitudinal and horizontal changes, or it can be horizontally averaged and describe longitudinal and vertical changes.

A three-dimensional system describes longitudinal, vertical, and horizontal changes.

Discharge (Q).— Volume of water that passes through a cross section of channel within a given period of time.

Dispersion and DQQ.— The redistribution of particles by the combined effects of shear (advection of fluid at different velocity and direction at different positions) and transverse diffusion (the scattering of particles by molecular and turbulent [eddy] motion).

Dynamic equation.—The dynamic equation is based on Newton's second law, conservation of momentum (or energy), which states that the summation of all external forces on a system is equal to the rate of change of momentum. External forces can be in the form of gravity, pressure, or friction. Further discussion of the dynamic equation and conservation of momentum can be found in Roberson and Crowe, 1980; Chow, 1959; Mahmood and Yevjevich, 1975; and most introductory texts on open-channel flow. See also "Flow conditions."

Eulerian-based Model.— Model based on a Eulerian approach, which is premised on Eulerian concepts and a fixed-coordinates system. Eulerian equations are a form of equation of motion based on Eulerian concepts, in which a fixed corrdinate system is used, and tangential and normal stresses accompanying deformation are ignored.

Finite Difference.—Finite-difference approximation is the representation of differential forms of equations (continuum) by corresponding finite-difference forms (discrete quantities). Finite-difference equations are derived by substituting difference quotients for derivatives in differential equations. The finite-difference method is an approximation method in which finite-difference expressions are substituted for differential equations to effect a solution.

Flow conditions.—Uniform flow means that the depth, width, and velocity are the same at every section of the channel. This is often stated as the assumption that the channel is prismatic. Steady flow means the velocity does not change with time at a point in the stream. Unsteady flow means that the velocity changes over time at a point in the stream. With fully dynamic flow, neither uniform nor steady assumptions can be made. Uniform flow can be modeled through the use of diffusion-wave simplification of the dynamic equation, which assumes that the effect from convective acceleration (or the increase in rate of flow caused by gravity) is negligible. Steady and uniform flow can be modeled with the kinetic wave simplification of the dynamic equation, which assumes that both convective acceleration and pressure effects (or effects from atmosphere or overlying water) are negligible—because flow is steady, pressure effects essentially cancel out. Fully dynamic flow must use the complete (fully) dynamic equation. Further discussion of these assumptions are given in Roberson and Crowe, 1980; Chow, 1959; Mahmood and Yevjevich, 1975; and most introductory texts on open-channel flow.

Fully dynamic flow.—See "Flow conditions"

Horizontally averaged.—See "Dimensions"

Hudson River Datums.—Several datums are used for hydrographic data in the Hudson River. In this report depths are referenced to National Geodetic Vertical Datum of 1929. Mean Low Water (MLW) refers to datums adopted by the National Ocean Service of the National Oceanic and Aeronautics Administration. Depths referenced to MLW are shown on topographic maps. In the past, Hudson River Datum refered to a datum used on hydrographic survey sheets for points downstream from Ossining (fig. 2). These datums are not static; they change with location in the river and with time and are updated every 19 years. More information on Hudson River datums can be obtained from the National Ocean Service, Tidal Datum Section (Milton Rutstein, National Ocean Service, written commun., 1989)

Kinetic wave model.—See "Flow conditions"

Longitudinal direction.—See "Dimensions"

Mean Low Water datum.—See "Hudson River Datums"

Mean Sea Level.—See "National Geodetic Vertical Datum of 1929"

Mgal/d.—Million gallons per day--A measure of discharge which approximately equals 1.55 ft^3/s (cubic feet per second). (See also conversion table at the beginning of this report.)

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, formerly called "Mean Sea Level of 1929." In this report all elevations are referenced to NGVD of 1929. Unless otherwise noted, negative elevations are feet below NGVD of 1929.

Negative flow.—In this report, negative flow is flow in the upstream direction. (See also "Positive flow".)

One-dimensional model.—See "Dimensions"

Percent exceedance.—Percent exceedance means that 80, 50, or 20 percent of all daily mean flows for that day have been greater than the the value shown.

Positive flow.—In this report, positive flow is flow in the downstream direction. (See also "Negative flow".)

River Mile (RM).—River mile is the distance, in miles, above the mouth of a river, determined from a line along the thalweg of the river. River miles in the Hudson River are miles above the Battery in New York City. (See also "Thalweg.")

Salt front.—The salt front is the saltwater/freshwater interface, defined in this study as the furthest upstream location where the chloride concentration exceeds 100 mg/L (milligrams per liter) at some point in the cross section.

Specific conductance.— A measure of the ability of a solution to conduct an electrical current over a 1-centimeter distance and adjusted to 25 degrees Celsius. Specific conductance is equivalent to the reciprocal of the resistance of the solution and is expressed in microsiemens per centimeter. Specific conductance is directly proportional to the chloride concentration and thus the salinity of the Hudson River.

Stage.— See “Water-surface elevation”

Steady-flow conditions.—Flow in which depth (and velocity) of flow in a given cross-section is constant with respect to time. (See also “Flow conditions”.)

Thalweg.—The deepest location in a cross section. River miles are generally measured along the line following the thalweg of a river.

Three dimensional.—See "Dimensions"

Tide.—Periodic variation in the water surface level of oceans, gulfs, bays, inlets, and tidal reaches of rivers, caused by the gravitational attraction of the sun and moon, the lunar effect being the more powerful. Various tidal terms follow: (1) diurnal tide—a tide having a period of 24.84 hours yielding one high water and one low water each lunar day, (2) semi-diurnal tide— a tide having a period of 12.42 hours yielding two nearly equal high waters and low waters in a lunar day, (3) mixed tide—a tide having both semidiurnal and diurnal components producing succeeding high waters that are appreciably different, (4) spring tide—tide of maximum range for a semidiurnal tide, occurring semimonthly usually 1 to 2 days after new and full moon, depending on geographic conditions, (5) neap tide—tide of minimum range for a semidiurnal tide; occurring semimonthly, usually 1 to 2 days after the moon is in quadrature, depending on geographic conditions, (6) slack tide—time interval of tidal flow during which the velocity is zero or nearly zero; in general, it is the transition period between flooding and ebbing or vice versa, (7) tide range—difference in height between consecutive high and low water levels.

Tidal stage.—Stage as it is affected by tide. (See “Tide” and “Water-surface elevation”.)

Transition zone.—The transition zone of an estuary is the area that can vary from water that ranges from salty to fresh throughout a year, depending on the conditions. The transition zone of the Hudson River extends from approximately Hastings-on-Hudson to New Hamburg, N.Y.

Two dimensional.—See "Dimensions"

Uniform flow conditions.—See "Flow conditions"

Unsteady-flow conditions.— Flow in which depth (and velocity) of flow in a given cross section varies with time. Unsteady flow can be alternating (flow direction can change) or unidirectional (flow is always in downstream direction).

Vertically averaged.— See “Dimensions”

Water-surface elevation.— The height (elevation) of the water surface above an established datum plane.

APPENDIX

Appendix I. Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

[Stage values are in feet above (+) or below (-) sea level. USGS, US Geological Survey; ft², square feet; ft, feet]

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
01358000	-14	187	75
	-10	587	88
	-8	785	94
	-6	977	96
	-4	1,173	99
	-2	1,373	103
	-1	1,504	134
	0	2,464	980
	2	4,508	1,070
	4	6,648	1,072
	6	8,798	1,075
	8	10,954	1,079
	10	13,114	1,082
	20	23,806	1,097
10000102	-10	4,005	460
	-9	4,479	480
	-8	4,924	525
	-6	5,978	560
	-4	7,130	598
	-3	7,740	621
	-2	8,380	640
	0	9,666	648
	2	10,970	655
	4	12,296	668
	6	13,642	680
	8	15,016	693
	10	16,416	705
	20	23,806	765
10000103	-10	3,526	510
	-8	4,556	520
	-7	5,076	525
	-6	5,631	557
	-4	6,774	575
	-2	7,934	586
	0	9,118	595
	2	10,318	605
	4	11,544	618
	6	12,798	632
	8	14,078	646
	10	15,388	659
	20	21,938	724
10000104	-10	8,129	520
	-8	9,265	573
	-6	10,423	582
	-4	11,593	587
	-2	12,773	592
	0	13,969	601
	2	15,173	610
	4	16,405	625
	6	17,671	644
	8	18,975	661
	10	20,315	679
	20	27,015	769
10000105	-10	9,197	900
	-8	11,021	920
	-6	12,941	976
	-4	14,921	1,013
	-2	16,997	1,055
	0	19,129	1,078
	2	21,309	1,100
	4	23,539	1,130
	6	25,831	1,163
	8	28,191	1,196
	10	30,683	1,230
	20	43,143	1,400
01359139	-10	9,200	900
	-8	11,000	920
	-6	12,900	980
	-4	14,900	1,010
	-2	17,000	1,060
	0	19,100	1,080
	2	21,300	1,100
	4	23,500	1,130
	6	25,800	1,170
	8	28,200	1,200
	10	30,600	1,230
	20	42,600	1,380
01359139	-10	9,200	900
	-8	11,000	920
	-6	12,900	980
	-4	14,900	1,010

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	-2	17,000	1,060
	0	19,100	1,080
	2	21,300	1,100
	4	23,500	1,130
	6	25,800	1,170
	8	28,200	1,200
	10	30,600	1,230
	20	42,600	1,380
1000020l	-10	19,600	980
	-8	21,600	980
	-6	23,500	980
	-4	25,500	990
	-2	27,500	990
	0	29,500	1,000
	2	31,500	1,000
	4	33,500	1,010
	6	35,500	1,010
	8	37,500	1,020
	10	39,600	1,030
10000301	-10	14,200	750
	-8	15,700	770
	-6	17,400	830
	-4	19,000	840
	-2	20,700	850
	0	22,400	860
	2	24,100	870
	4	25,900	900
	6	27,700	930
	8	29,600	970
	10	31,600	1,000
10000401	-10	14,100	860
	-8	15,900	980
	-6	18,100	1,160
	-4	20,400	1,170
	-2	22,800	1,180
	0	25,100	1,190
	2	27,500	1,200
	4	29,900	1,220
	6	32,400	1,250
	8	34,900	1,280
	10	37,900	1,700

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
20000501	-5	0	0
	0	5,200	1,200
	2	9,200	1,600
	10	30,000	2,400
20000601	-10	1,600	600
	0	20,000	2,000
	2	24,800	2,400
	10	50,000	3,200
10000401	-10	14,100	860
	-8	15,900	980
	-6	18,100	1,160
	-4	20,400	1,170
	-2	22,800	1,180
	0	25,100	1,190
	2	27,500	1,200
	4	29,900	1,220
	6	32,400	1,250
	8	34,900	1,280
	10	37,900	1,700
10000701	-10	15,800	730
	-8	17,300	770
	-6	18,900	890
	-4	20,800	990
	-2	22,900	1,170
	0	25,500	1,410
	2	28,400	1,460
	4	31,400	1,530
	6	34,500	1,620
	8	37,800	1,700
	10	41,700	2,150
10000801	-10	18,400	930
	-8	20,300	950
	-6	22,200	980
	-4	124,200	50
	-2	126,400	120
	0	128,700	160
	2	131,000	180
	4	133,400	230
	6	135,900	290
	8	138,500	350
	10	141,600	720

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
10000901	-10	25,600	1390
	-8	28,400	1440
	-6	31,600	1700
	-4	35,300	1880
	-2	39,100	1910
	0	43,200	2160
	2	47,600	2230
	4	52,200	2310
	6	57,100	2570
	8	62,200	2570
	10	67,400	2580
20001001	-10	0	0
	-2	600	450
	0	3,300	1,200
	2	6,000	1,500
	4	10,800	2,100
	6	21,000	4,800
	8	33,000	5,400
	10	45,000	6,000
20001101	-10	2,200	500
	-2	12,600	1,500
	0	15,000	1,800
	2	20,000	2,100
	4	24,000	2,500
	6	32,000	3,000
	8	37,000	3,600
	10	45,000	3,900
10000901	-10	25,600	1,390
	-8	28,400	1,440
	-6	31,600	1,700
	-4	35,300	1,880
	-2	39,100	1,910
	0	43,200	2,160
	2	47,600	2,230
	4	52,200	2,310
	6	57,100	2,570
	8	62,200	2,570
	10	67,400	2,580
10001201	-10	22,800	1,440
	-8	25,700	1,480
	-6	28,800	1,600
	-4	32,200	1,820
	-2	36,000	1,910
	0	39,900	1,990
	2	43,900	2,080
	4	48,200	2,160
	6	52,600	2,250
	8	56,700	2,330
	10	62,700	2,770
10001301	-10	31,700	1,580
	-8	34,900	1,680
	-6	38,400	1,790
	-4	42,100	1,930
	-2	46,000	2,020
	0	50,300	2,090
	2	54,400	2,150
	4	58,800	2,220
	6	63,300	2,280
	8	67,400	2,340
	10	74,200	3,150
20001401	-3	2,000	1,000
	0	6,000	2,000
	10	26,000	2,000
20001501	-6	1,600	1,600
	-2	10,000	2,400
	0	20,000	4,000
	10	70,000	6,000
10001301	-10	31,700	1,580
	-8	34,900	1,680
	-6	38,400	1,790
	-4	42,100	1,930
	-2	46,000	2,020
	0	50,300	2,090
	2	54,400	2,150
	4	58,800	2,220
	6	63,300	2,280
	8	67,400	2,340
	10	74,200	3,150
10001601	-10	35,300	2,620
	-8	40,600	2,700
	-6	46,100	2,780
	-4	51,800	2,900
	-2	57,700	3,010
	0	63,700	3,030
	2	69,800	3,040

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	4	75,900	3,060
	6	82,000	3,080
	8	88,200	3,090
	10	94,400	3,110
10001701	-10	25,000	970
	-8	27,100	1,170
	-6	29,700	1,610
	-4	33,700	2,300
	-2	39,300	3,000
	0	45,500	3,250
	2	52,100	3,270
	4	58,600	3,280
	6	65,200	3,290
	8	71,800	3,310
	10	78,400	3,320
01361450	-10	38,000	1,610
	-8	41,200	1,670
	-6	44,700	1,740
	-4	48,200	1,820
	-2	52,000	1,970
	0	56,000	2,030
	2	60,100	2,070
	4	64,300	2,110
	6	68,600	2,160
	8	73,900	3,220
	10	81,400	4,270
20001901	-10	500	200
	-2	1,800	300
	0	3,000	800
	2	5,300	1,100
	10	15,000	1,200
20002001	-10	1,000	400
	-2	3,300	500
	0	5,100	1,000
	2	8,000	1,500
	10	20,200	1,600
01361450	-10	38,000	1,610
	-8	41,200	1,670
	-6	44,700	1,740
	-4	48,200	1,820
	-2	52,000	1,970

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	0	56,000	2,030
	2	60,100	2,070
	4	64,300	2,110
	6	68,600	2,160
	8	73,900	3,220
	10	81,400	4,270
10002101	-10	41,200	2,120
	-8	45,500	2,190
	-6	50,000	2,340
	-4	54,900	2,760
	-2	61,300	3,690
	0	69,000	3,860
	2	76,800	3,880
	4	84,600	3,900
	6	92,400	3,920
	8	100,000	3,940
	10	108,000	3,950
01362187	-10	39,000	2,110
	-8	43,300	2,170
	-6	47,700	2,240
	-4	52,300	2,360
	-2	57,400	2,840
	0	63,900	3,340
	2	70,600	3,370
	4	77,400	3,400
	6	84,200	3,410
	8	91,000	3,430
	10	97,900	3,450
20002301	-10	500	200
	-2	1,800	300
	0	3,000	800
	2	5,300	1,100
	10	15,000	1,200
20002401	-10	1,000	400
	-2	3,300	500
	0	5,100	1,000
	2	8,000	1,500
	10	20,200	1,600
01362187	-10	39,000	2,110
	-8	43,300	2,170
	-6	47,700	2,240
	-4	52,300	2,360

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	-2	57,400	2,840
	0	63,900	3,340
	2	70,600	3,370
	4	77,400	3,400
	6	84,200	3,410
	8	91,000	3,430
	10	97,900	3,450
10002501	-10	43,300	2,200
	-8	47,700	2,250
	-6	52,300	2,300
	-4	57,100	2,850
	-2	63,700	3,520
	0	71,400	4,320
	2	80,400	4,340
	4	89,600	4,360
	6	98,800	4,380
	8	108,000	4,400
	10	118,000	4,420
10002501	-10	43,300	2,200
	-8	47,700	2,250
	-6	52,300	2,300
	-4	57,100	2,850
	-2	63,700	3,520
	0	71,400	4,320
	2	80,400	4,340
	4	89,600	4,360
	6	98,800	4,380
	8	108,000	4,400
	10	118,000	4,420
01364832	-10	57,291	3,117
	-8	63,557	3,149
	-6	69,897	3,190
	-4	76,453	3,358
	-2	83,173	3,362
	0	89,900	3,365
	2	96,633	3,368
	4	3,382	3,390
	6	10,202	3,430
	8	17,102	3,470
	10	24,082	3,510
01364840	-10	57,200	3,140
	-8	63,500	3,190
	-6	70,000	3,280

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	-4	76,700	3,380
	-2	83,500	3,470
	0	90,500	3,530
	2	97,600	3,550
	4	105,000	3,570
	6	112,000	3,640
	8	119,000	3,730
	10	127,000	3,800
10002701	-10	65,000	2,790
	-8	70,700	2,880
	-6	76,600	3,030
	-4	83,500	3,890
	-2	91,400	3,970
	0	99,300	3,980
	2	107,000	3,990
	4	115,000	4,010
	6	123,000	4,050
	8	132,000	4,090
	10	140,000	4,130
01372009	-10	72,400	2,600
	-8	78,000	2,930
	-6	84,200	3,270
	-4	91,000	3,610
	-2	98,600	3,960
	0	107,000	4,300
	2	116,000	4,400
	4	124,000	4,440
	6	133,000	4,480
	8	142,000	4,520
	10	152,000	4,980
01372009	-10	72,400	2,600
	-8	78,000	2,930
	-6	84,200	3,270
	-4	91,000	3,610
	-2	98,600	3,960
	0	107,000	4,300
	2	116,000	4,400
	4	124,000	4,440
	6	133,000	4,480
	8	142,000	4,520
	10	152,000	4,980
0137200910	-10	65,000	2,790
	-8	70,700	2,880

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	-6	76,600	3,030
	-4	83,500	3,890
	-2	91,400	3,970
	0	99,300	3,980
	2	107,000	3,990
	4	115,000	4,010
	6	123,000	4,050
	8	132,000	4,090
	10	140,000	4,130
10002901	-10	90,000	2,220
	-8	94,400	2,240
	-6	99,000	2,290
	-4	104,000	2,990
	-2	111,000	3,840
	0	120,000	4,910
	2	131,000	6,150
	4	144,000	6,180
	6	156,000	6,220
	8	169,000	6,260
	10	181,000	6,300
10003001	-10	85,300	2,670
	-8	90,700	2,680
	-6	96,000	2,690
	-4	101,000	2,710
	-2	107,000	2,720
	0	112,000	2,730
	2	118,000	2,760
	4	123,000	2,780
	6	129,000	2,810
	8	135,000	2,840
	10	140,000	2,860
0137204020	-10	88,500	2,380
	-8	93,200	2,400
	-6	98,100	2,430
	-4	103,000	2,460
	-2	108,000	2,490
	0	113,000	2,500
	2	118,000	2,510
	4	123,000	2,520
	6	128,000	2,540
	8	133,000	2,560
	10	138,000	2,570
0137204020	-10	88,500	2,380
	-8	93,200	2,400
	-6	98,100	2,430
	-4	103,000	2,460
	-2	108,000	2,490
	0	113,000	2,500
	2	118,000	2,510
	4	123,000	2,520
	6	128,000	2,540
	8	133,000	2,560
	10	138,000	2,570
10003201	-10	99,200	1,690
	-8	103,000	1,700
	-6	106,000	1,730
	-4	110,000	1,760
	-2	113,000	1,770
	0	117,000	1,780
	2	120,000	1,790
	4	124,000	1,800
	6	128,000	1,810
	8	131,000	1,820
	10	135,000	1,830
10003301	-10	102,000	2,420
	-8	107,000	2,460
	-6	111,000	2,510
	-4	117,000	2,540
	-2	122,000	2,600
	0	127,000	2,620
	2	132,000	2,640
	4	137,000	2,650
	6	143,000	2,660
	8	148,000	2,670
	10	153,000	2,680
01372055	-10	109,000	2,540
	-8	115,000	2,550
	-6	120,000	2,570
	-4	125,000	2,580
	-2	130,000	2,590
	0	135,000	2,630
	2	140,000	2,650
	4	146,000	2,660
	6	151,000	2,670

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	8	156,000	2,690
	10	162,000	2,700
01372055	-10	109,000	2,540
	-8	115,000	2,550
	-6	120,000	2,570
	-4	125,000	2,580
	-2	130,000	2,590
	0	135,000	2,630
	2	140,000	2,650
	4	146,000	2,660
	6	151,000	2,670
	8	156,000	2,690
	10	162,000	2,700
10003501	-10	102,000	2,390
	-8	107,000	2,400
	-6	112,000	2,430
	-4	116,000	2,460
	-2	121,000	2,480
	0	126,000	2,510
	2	131,000	2,540
	4	137,000	2,550
	6	142,000	2,570
	8	147,000	2,580
	10	152,000	2,600
01372059	-10	105,000	2,230
	-8	109,000	2,240
	-6	114,000	2,260
	-4	118,000	2,280
	-2	123,000	2,440
	0	128,000	2,460
	2	133,000	2,490
	4	138,000	2,510
	6	143,000	2,520
	8	148,000	2,540
	10	153,000	2,550
01372059	-12	101,000	2,220
	-10	105,000	2,230
	-8	109,000	2,240
	-6	114,000	2,260
	-4	118,000	2,280
	-2	123,000	2,440
	0	128,000	2,440
	2	133,000	2,490
	4	138,000	2,510
	6	143,000	2,520
	8	148,000	2,540
	10	153,000	2,550
10000162	-20	76,384	4,200
	-15	97,684	4,320
	-10	119,634	4,460
	-8	128,574	4,480
	-6	137,570	4,515
	-4	146,606	4,520
	-2	155,652	4,525
	0	164,707	4,530
	2	173,782	4,545
	4	182,887	4,560
	6	192,027	4,580
	8	201,207	4,600
	10	210,422	4,615
	15	233,609	4,660
	20	257,010	4,700
10000163	-20	93,253	2,210
	-15	104,328	2,220
	-10	115,453	2,230
	-8	119,921	2,238
	-6	124,405	2,246
	-4	128,905	2,254
	-2	133,421	2,262
	0	137,953	2,270
	2	142,498	2,275
	4	147,092	2,319
	6	151,774	2,363
	8	156,544	2,407
	10	161,401	2,450
	15	174,351	2,730
	20	188,701	3,010
01372500	-20	89,400	2,950
	-15	104,445	3,068
	-10	120,085	3,188
	-8	126,508	3,235
	-6	133,014	3,271
	-4	139,565	3,280
	-2	146,135	3,290
	0	152,735	3,300
	2	159,346	3,311
	4	165,980	3,323

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	6	172,637	3,334
	8	179,316	3,345
	10	186,019	3,658
	15	204,644	3,792
	20	223,936	3,925
01372500	-20	89,400	2,950
	-15	104,445	3,068
	-10	120,085	3,188
	-8	126,508	3,235
	-6	133,014	3,271
	-4	139,565	3,280
	-2	146,135	3,290
	0	152,735	3,300
	2	159,346	3,311
	4	165,980	3,323
	6	172,637	3,334
	8	179,316	3,345
	10	186,019	3,658
	15	204,644	3,792
	20	223,936	3,925
10000172	-20	69,167	3,375
	-15	86,780	3,660
	-10	105,354	3,770
	-8	112,990	3,865
	-6	120,814	3,960
	-4	128,830	4,055
	-2	137,944	5,060
	0	148,094	5,090
	2	158,280	5,095
	4	168,470	5,096
	6	178,664	5,097
	8	188,858	5,098
	10	199,056	5,100
	15	224,644	5,135
	20	250,406	5,170
01372575	-15	83,488	4,183
	-10	104,634	4,250
	-8	113,234	4,269
	-6	121,834	4,288
	-4	130,434	4,308
	-2	139,034	4,328
	0	147,634	4,347
	2	156,374	4,354
	4	165,114	4,361
	6	173,854	4,368
	8	182,594	4,375
	10	191,334	4,382
	15	213,474	4,876
01372575	-15	83,488	4,183
	-10	104,634	4,250
	-8	113,234	4,269
	-6	121,834	4,288
	-4	130,434	4,308
	-2	139,034	4,328
	0	147,634	4,347
	2	156,374	4,354
	4	165,114	4,361
	6	173,854	4,368
	8	182,594	4,375
	10	191,334	4,382
	15	213,474	4,876
10000183	-20	55,533	4,383
	-15	77,948	4,583
	-10	101,083	4,691
	-8	110,535	4,760
	-6	120,115	4,820
	-4	130,003	5,075
	-2	140,471	5,389
	-1	146,784	7,238
	0	154,030	7,254
	2	168,618	7,335
	4	183,314	7,362
	6	198,066	7,390
	8	212,874	7,418
	10	227,738	7,445
	15	265,428	7,632
	20	304,058	7,820
10000184	-20	63,833	4,225
	-15	89,858	4,440
	-10	108,380	4,820
	-8	118,120	4,920
	-6	128,170	5,130
	-4	139,100	5,800
	-2	152,650	7,750
	0	168,850	8,450
	2	185,830	8,530
	4	202,940	8,580
	6	220,150	8,630

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	8	237,460	8,680
	10	254,870	8,730
	15	298,646	8,780
	20	342,670	8,830
10000184	-20	63,833	4,225
	-15	89,858	4,440
	-10	108,380	4,820
	-8	118,120	4,920
	-6	128,170	5,130
	-4	139,100	5,800
	-2	152,650	7,750
	0	168,850	8,450
	2	185,830	8,530
	4	202,940	8,580
	6	220,150	8,630
	8	237,460	8,680
	10	254,870	8,730
	15	298,646	8,780
	20	342,670	8,830
10000193	-20	84,987	2,117
	-14	98,493	2,386
	-10	108,493	2,615
	-8	113,733	2,625
	-6	118,990	2,632
	-4	124,262	2,640
	-2	129,550	2,648
	0	134,853	2,655
	2	140,173	2,665
	4	145,509	2,671
	6	150,587	2,677
	8	156,216	2,682
	10	161,586	2,688
	15	175,041	2,694
	20	188,526	2,700
10000193	-20	84,987	2,117
	-14	98,493	2,386
	-10	108,493	2,615
	-8	113,733	2,625
	-6	118,990	2,632
	-4	124,262	2,640
	-2	129,550	2,648
	0	134,853	2,655
	2	140,173	2,665
	4	145,509	2,671
	6	150,587	2,677
	8	156,216	2,682
	10	161,586	2,688
	15	175,041	2,694
	20	188,526	2,700
10000202	-20	89,440	2,041
	-15	99,688	2,060
	-10	109,995	2,063
	-8	114,124	2,066
	-6	118,260	2,070
	-4	122,404	2,074
	-2	126,555	2,077
	0	130,712	2,080
	1	132,792	2,080
	4	139,160	2,165
	6	143,542	2,218
	8	148,072	2,272
	10	152,670	2,325
	15	164,362	2,452
	20	176,942	2,580
10000203	-20	80,200	2,110
	-15	90,925	2,180
	-10	102,000	2,250
	-8	106,528	2,278
	-6	111,113	2,307
	-4	115,755	2,335
	-2	120,453	2,363
	-1	123,435	3,600
	0	127,113	3,755
	2	134,653	3,785
	4	142,239	3,801
	6	149,858	3,818
	8	157,510	3,834
	10	165,194	3,850
	15	184,564	3,898
	20	204,172	3,945
10000203	-20	80,200	2,110
	-15	90,925	2,180
	-10	102,000	2,250
	-8	106,528	2,278
	-6	111,113	2,307
	-4	115,755	2,335
	-2	120,453	2,363
	-1	123,435	3,600

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	0	127,113	3,755
	2	134,653	3,785
	4	142,239	3,801
	6	149,858	3,818
	8	157,510	3,834
	10	165,194	3,850
	15	184,564	3,898
	20	204,172	3,945
10000204	-14	104,771	2,021
	-12	108,836	2,045
	-10	112,951	2,070
	-8	117,115	2,096
	-6	121,340	2,130
	-4	125,637	2,167
	-2	130,009	2,205
	0	134,458	2,243
	2	138,981	2,280
	4	143,578	2,316
	6	148,246	2,352
	8	153,183	2,584
	10	158,579	2,810
	12	164,222	2,833
	14	169,911	2,856
	16	175,645	2,878
	18	181,424	2,901
10000213	-20	151,400	1,535
	-15	159,150	1,565
	-10	167,050	1,595
	-8	170,255	1,610
	-6	173,513	1,648
	-4	176,813	1,652
	-2	180,121	1,656
	0	183,437	1,660
	2	186,803	1,706
	4	190,260	1,751
	6	193,808	1,797
	8	197,448	1,843
	10	201,179	1,888
	15	210,734	1,934
	20	220,519	1,980
10000214	-14	162,422	1,828
	-12	166,096	1,847
	-10	169,808	1,865
	-8	173,557	1,884
	-6	177,360	1,919
	-4	181,316	2,050
	-2	185,638	2,248
	0	190,287	2,365
	2	195,055	2,401
	4	199,877	2,418
	6	204,728	2,432
	8	209,710	2,553
	10	214,948	2,688
	12	220,366	2,729
	14	225,866	2,771
	16	231,449	2,812
	18	237,115	2,854
10000215	-14	162,235	1,612
	-12	165,481	1,634
	-10	168,766	1,650
	-8	172,085	1,676
	-6	175,497	1,743
	-4	179,085	1,845
	-2	182,879	1,952
	0	186,899	2,072
	2	191,139	2,160
	4	195,507	2,201
	6	199,940	2,232
	8	204,558	2,383
	10	209,467	2,523
	12	214,523	2,532
	14	219,597	2,542
	16	224,690	2,551
	18	229,802	2,561
01374019	-20	84,512	2,005
	-15	94,587	2,030
	-10	104,762	2,045
	-8	108,852	2,050
	-6	112,962	2,060
	-4	117,092	2,070
	-2	121,242	2,080
	0	125,462	2,100
	2	129,677	2,110
	4	133,877	2,112
	6	138,107	2,115
	8	142,348	2,118
	10	146,588	2,120
	15	157,512	2,255
	20	168,962	2,390

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
01374019	-20	84,512	2,005
	-15	94,587	2,030
	-10	104,762	2,045
	-8	108,852	2,050
	-6	112,962	2,060
	-4	117,092	2,070
	-2	121,242	2,080
	0	125,462	2,100
	2	129,677	2,110
	4	133,877	2,112
	6	138,107	2,115
	8	142,348	2,118
	10	146,588	2,120
	15	157,512	2,255
	20	168,962	2,390
0137402390	-15	105,654	1,414
	-13	108,491	1,423
	-11	111,346	1,431
	-9	114,216	1,439
	-7	117,105	1,449
	-5	120,014	1,460
	-4	121,484	1,481
	-3	122,966	1,484
	-2	124,453	1,488
	-1	125,943	1,492
	0	127,437	1,496
	2	130,438	1,507
	4	133,466	1,521
	5	134,990	1,527
	6	136,521	1,534
	7	138,058	1,541
	8	139,603	1,548
	9	141,154	1,555
	10	142,712	1,562
	20	158,200	1,625
10000214	-15	117,875	1,850
	-13	121,586	1,861
	-11	125,324	1,877
	-9	129,096	1,896
	-7	132,921	1,938
	-5	136,879	1,994
	-4	138,875	1,998
	-3	140,874	2,001
	-2	142,876	2,004
	-1	144,881	2,007
	0	146,889	2,010
	2	150,924	2,025
	4	154,988	2,040
	5	157,032	2,047
	6	159,083	2,055
	7	161,141	2,062
	8	163,208	2,070
	9	165,281	2,077
	10	167,363	2,085
	20	186,800	2,160
10000215	-15	104,829	2,256
	-13	109,370	2,285
	-11	113,956	2,301
	-9	118,579	2,326
	-7	123,278	2,373
	-5	128,062	2,401
	-4	130,465	2,404
	-3	132,871	2,408
	-2	135,281	2,412
	-1	137,695	2,416
	0	140,114	2,420
	2	144,977	2,443
	4	149,886	2,466
	5	152,357	2,478
	6	154,841	2,489
	7	157,335	2,501
	8	159,842	2,512
	9	162,359	2,524
	10	164,889	2,535
	20	189,000	2,642
10000216	-15	121,349	3,911
	-13	129,201	3,943
	-11	137,120	3,974
	-9	145,093	3,999
	-7	153,221	4,205
	-6	157,621	4,399
	-5	162,073	4,505
	-4	166,602	4,553
	-2	175,719	4,564
	-1	180,286	4,569
	0	184,858	4,575
	2	194,021	4,592
	4	203,227	4,615
	5	207,847	4,626

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	6	212,479	4,638
	7	217,122	4,649
	8	221,827	4,761
	9	226,644	4,872
	10	231,571	4,984
	20	277,000	5,933
01374320	-11	121,073	3,490
	-9	128,073	3,511
	-7	135,107	3,523
	-6	138,640	3,544
	-5	142,195	3,566
	-4	145,763	3,569
	-3	149,334	3,572
	-2	152,908	3,576
	-1	156,485	3,579
	0	160,065	3,582
	2	167,237	3,593
	4	174,439	3,608
	5	178,051	3,616
	6	181,671	3,624
	7	185,299	3,632
	8	188,934	3,639
	9	192,651	3,794
	10	196,522	3,948
	15	230,000	4,047
01374320	-11	121,073	3,490
	-9	128,073	3,511
	-7	135,107	3,523
	-6	138,640	3,544
	-5	142,195	3,566
	-4	145,763	3,569
	-3	149,334	3,572
	-2	152,908	3,576
	-1	156,485	3,579
	0	160,065	3,582
	2	167,237	3,593
	4	174,439	3,608
	5	178,051	3,616
	6	181,671	3,624
	7	185,299	3,632
	8	188,934	3,639
	9	192,651	3,794
	10	196,522	3,948
	15	230,000	4,047

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
10000217	-15	122,618	2,801
	-13	128,368	2,949
	-11	134,464	3,145
	-9	140,924	3,300
	-7	148,039	3,787
	-6	152,073	4,474
	-5	157,103	5,079
	-4	162,223	5,131
	-2	172,491	5,137
	-1	177,629	5,139
	0	182,770	5,142
	2	193,070	5,168
	4	203,452	5,214
	5	208,677	5,237
	6	213,925	5,260
	7	219,197	5,283
	8	224,491	5,306
	9	229,808	5,329
	10	235,148	5,352
	15	261,000	5,495
10000218	-13	100,468	5,338
	-11	112,165	6,294
	-9	125,487	6,722
	-7	139,365	6,990
	-6	146,381	7,042
	-5	153,449	7,094
	-4	160,584	7,138
	-3	167,724	7,143
	-2	174,870	7,149
	-1	182,021	7,154
	0	189,178	7,160
	2	203,508	7,172
	4	217,865	7,185
	5	225,054	7,192
	6	232,249	7,199
	7	239,451	7,205
	8	246,660	7,212
	9	254,086	7,640
	10	261,940	8,068
	15	285,000	9,760
0137448530	-12	72,000	15,000
	-10	112,000	15,130
	-8	143,000	15,205
	-6	174,098	15,257

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	-5	189,368	15,284
	-4	204,654	15,286
	-3	219,941	15,289
	-2	235,231	15,291
	-1	250,523	15,293
	0	265,817	15,295
	2	296,413	15,300
	4	327,028	15,315
	5	342,346	15,323
	6	357,673	15,330
	7	373,083	15,490
	8	388,652	15,650
	9	404,383	15,810
	10	420,273	15,970
0137448530	-12	72,000	15,000
	-10	112,000	15,130
	-8	143,000	15,205
	-6	174,098	15,257
	-5	189,368	15,284
	-4	204,654	15,286
	-3	219,941	15,289
	-2	235,231	15,291
	-1	250,523	15,293
	0	265,817	15,295
	2	296,413	15,300
	4	327,028	15,315
	5	342,346	15,323
	6	357,673	15,330
	7	373,083	15,490
	8	388,652	15,650
	9	404,383	15,810
	10	420,273	15,970
	15	495,000	16,810
10000219	-15	56,622	3,095
	-13	63,298	3,558
	-11	74,239	7,043
	-9	89,341	8,973
	-7	117,960	14,174
	-6	132,157	14,221
	-5	146,411	14,287
	-4	160,767	14,375
	-3	175,208	14,445
	-2	189,658	14,454
	-1	204,116	14,463
	0	218,583	14,471
	2	247,542	14,486
	4	276,525	14,498
	5	291,026	14,504
	6	305,533	14,510
	7	320,046	14,516
	8	334,565	14,522
	9	349,089	14,528
	10	363,620	14,534
01374486	-12	104,753	5,195
	-11	110,052	5,366
	-9	120,992	5,539
	-7	133,431	6,279
	-6	139,739	6,336
	-5	146,091	6,369
	-4	152,477	6,402
	-3	158,918	6,484
	-2	165,422	6,506
	-1	171,939	6,527
	0	178,474	6,544
	2	191,588	6,565
	4	204,727	6,574
	5	211,303	6,579
	6	217,885	6,584
	7	224,471	6,588
	8	231,062	6,593
	9	237,657	6,598
	10	244,257	6,603
01374486	-12	104,753	5,195
	-11	110,052	5,366
	-9	120,992	5,539
	-7	133,431	6,279
	-6	139,739	6,336
	-5	146,091	6,369
	-4	152,477	6,402
	-3	158,918	6,484
	-2	165,422	6,506
	-1	171,939	6,527
	0	178,474	6,544
	2	191,588	6,565
	4	204,727	6,574
	5	211,303	6,579
	6	217,885	6,584
	7	224,471	6,588
	8	231,062	6,593
	9	237,657	6,598

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	10	244,257	6,603
10000220	-15	74,501	6,455
	-13	87,504	6,547
	-11	100,878	7,151
	-9	119,392	9,812
	-7	139,120	9,903
	-6	149,040	9,936
	-5	158,992	9,968
	-4	168,999	10,046
	-3	179,090	10,136
	-2	189,227	10,140
	-1	199,369	10,143
	0	209,513	10,147
	2	229,816	10,158
	4	250,150	10,175
	5	260,329	10,184
	6	270,517	10,192
	7	280,748	10,269
	8	291,055	10,346
	9	301,440	10,423
	10	311,902	10,500
10000221	-15	64,820	4,841
	-13	76,667	7,851
	-11	96,287	10,251
	-9	119,230	11,903
	-7	143,798	12,448
	-6	156,318	12,593
	-5	169,002	12,688
	-4	181,695	12,697
	-3	194,396	12,705
	-2	207,105	12,713
	-1	219,822	12,722
	0	232,548	12,730
	2	258,023	12,745
	4	283,528	12,760
	5	296,292	12,768
	6	309,063	12,775
	7	321,842	12,783
	8	334,628	12,790
	9	347,422	12,798
	10	360,223	12,805
10000222	-8	113,723	11,793
	-7	125,807	12,630
	-6	138,591	12,683
	-5	151,407	12,818
	-4	164,227	12,822
	-3	177,051	12,827
	-2	189,880	12,831
	-1	202,714	12,836
	0	215,552	12,840
	2	241,252	12,860
	4	266,992	12,880
	5	279,877	12,890
	6	292,772	12,900
	7	305,677	12,910
	8	318,592	12,920
	9	331,517	12,930
	10	344,452	12,940
10000223	-15	97,914	6,337
	-13	110,657	6,399
	-11	123,562	6,512
	-9	136,659	6,585
	-7	150,004	6,764
	-6	156,785	6,799
	-5	163,623	6,877
	-4	170,501	6,880
	-3	177,382	6,883
	-2	184,267	6,887
	-1	191,156	6,890
	0	198,047	6,893
	2	211,841	6,900
	4	225,651	6,911
	5	232,565	6,916
	6	239,483	6,921
	7	246,408	6,927
	8	253,337	6,932
	9	260,272	6,938
	10	268,411	9,340
10000224	-15	86,546	4,097
	-13	94,854	4,201
	-11	103,328	4,280
	-9	111,948	4,339
	-7	120,691	4,410
	-6	125,122	4,452
	-5	129,607	4,518
	-4	134,267	4,721
	-3	140,156	5,999
	-2	146,236	6,057
	-1	152,294	6,060

Appendix I. (continued) Cross-sectional geometry data used in BRANCH flow model of the Hudson River between Green Island and Hastings-on-Hudson, N.Y.

USGS station or cross section	Stage	Channel area (ft^2)	Channel width (ft)
	0	158,356	6,063
	2	170,489	6,070
	4	182,648	6,089
	5	188,742	6,098
	6	194,845	6,108
	7	200,957	6,117
	8	207,079	6,127
	9	213,304	6,324
	10	219,726	6,521
01376303	-15	83,681	3,674
	-13	91,184	3,823
	-11	98,943	3,936
	-9	106,929	4,050
	-7	115,148	4,192
	-6	119,405	4,322
	-5	123,792	4,452
	-4	128,248	4,459
	-3	132,711	4,467
	-2	137,181	4,474
	-1	141,659	4,489
	0	146,145	4,489
	2	155,141	4,511
	4	164,174	4,522
	5	168,698	4,527
	6	173,227	4,532
	7	177,762	4,537
	8	182,302	4,542
	9	186,863	4,579
	10	191,460	4,616

Appendix II. Initial condition card input for Hudson River branches between Green Island and Hastings-on-Hudson for May 9-10, 1990
[Locations are shown in figs. 2 and 3; ft, feet; ft^3/s, cubic feet per second. Water temperature 56 ˚ Fahrenheit]

Source node	Outlet node	No. of cross sections	Stage (ft)	Discharge (cubic ft per second)	Segment length (ft)	Water temperature (˚F)	Flow resistance coefficient (*eta*)	Segment orientation[1]	Momentum coefficient
1	2	6	BR1--GREEN ISLAND TO ALBANY						
			4.88	18090	9100	56.0	0.025	196.0	1.000
			4.78	20500	10560	56.0	0.025	188.5	1.000
			4.66	24000	12144	56.0	0.025	205.5	1.000
			4.55	28000	7920	56.0	0.025	212.0	1.000
			4.46	31000	5300	56.0	0.025	199.0	1.000
			4.40	34000				199.0	1.000
2	4	4	BR2--ALBANY TO CASTLETON-ON-HUDSON						
			4.40	34000.	12140.	56.0	0.025	191.5	1.000
			4.25	39000.	6340.	56.0	0.024	169.0	1.000
			4.20	42000.	24800.	56.0	0.024	186.0	1.000
			3.91	54000.				186.0	1.000
3	4	2	BR3--STORAGE NEAR CASTLETON-ON-HUDSON						
			3.91	250.	8000.	56.0	0.025	186.0	1.000
			2.99	250.				186.0	1.000
4	6	4	BR4--CASTLETON-ON-HUDSON TO SCHODACK LANDING						
			3.91	54000.	22700.	56.0	0.024	203.0	1.000
			3.66	67000.	12150.	56.0	0.023	180.0	1.000
			3.52	74000.	7390.	56.0	0.023	180.0	1.000
			3.44	79000.				180.0	1.000
5	6	2	BR5--STORAGE NEAR SCHODACK LANDING						
			3.44	250.	24000.	56.0	0.025	180.0	1.000
			2.97	250.				180.0	1.000

Appendix II. (continued) Initial condition card input for Hudson River branches between Green Island and Hastings-on-Hudson for May 9-10, 1990

Source node	Outlet node	No. of cross sections	Stage (ft)	Discharge (cubic ft per second)	Segment length (ft)	Water temperature (°F)	Flow resistance coefficient (*eta*)	Segment orientation[1]	Momentum coefficient
6	8	3	BR6--SCHODACK LANDING TO STOCKPORT						
			3.44	79000.	20060.	56.0	0.023	190.0	1.000
			3.22	92000.	22710.	56.0	0.022	170.0	1.000
			2.97	107000.				170.0	1.000
7	8	2	BR7--STORAGE NEAR STOCKPORT						
			2.97	250.	14000.	56.0	0.025	170.0	1.000
			2.96	250.				170.0	1.000
8	10	4	BR8--STOCKPORT TO CATSKILL						
			2.97	107000.	22700.	56.0	0.022	194.0	1.000
			2.71	122000.	15310.	56.0	0.021	216.0	1.000
			2.55	133000.	7390.	56.0	0.021	187.5	1.000
			2.46	137000.				187.5	1.000
9	10	2	BR9--STORAGE NEAR CATSKILL						
			2.46	250.	13000.	56.0	0.025	187.5	1.000
			2.92	250.				187.5	1.000
10	12	3	BR10--CATSKILL TO WEST CAMP						
			2.46	137000.	13730.	56.0	0.02	212.0	1.000
			2.32	147000.	26930.	56.0	0.019	203.5	1.000
			2.01	166000.				203.5	1.000
11	12	2	BR11--STORAGE NEAR WEST CAMP						
			2.01	250.	13000.	56.0	0.025	203.5	1.000
			2.88	250.				203.5	1.000
12	13	2	BR12--WEST CAMP TO SAUGERTIES						
			2.01	166000.	14780.	56.0	0.018	188.0	1.000
			1.85	177000.				188.0	1.000

Appendix II. (continued) Initial condition card input for Hudson River branches between Green Island and Hastings-on-Hudson for May 9-10, 1990

Source node	Outlet node	No. of cross sections	Stage (ft)	Discharge (cubic ft per second)	Segment length (ft)	Water temperature (˚F)	Flow resistance coefficient (*eta*)	Segment orientation[1]	Momentum coefficient
13	14	5	BR13--SAUGERTIES TO KINGSTON						
			1.85	177000.	21120.	56.0	0.017	190.0	1.000
			1.63	192000.	5280.	56.0	0.017	196.0	1.000
			1.53	197000.	13730.	56.0	0.017	191.0	1.000
			1.35	208000.	16900.	56.0	0.017	188.0	1.000
			1.15	220000.				188.0	1.000
14	15	5	BR14--KINGSTON TO HYDE PARK						
			1.15	220000.	7400.	56.0	0.015	165.0	1.000
			1.05	225000.	13720.	56.0	0.015	165.0	1.000
			0.85	234000.	10560.	56.0	0.015	191.5	1.000
			0.73	240000.	13730.	56.0	0.015	180.0	1.000
			0.59	248000.				180.0	1.000
15	16	4	BR15--HYDE PARK TO POUGHKEEPSIE						
			0.59	248000.	13730.	56.0	0.015	182.5	1.000
			0.53	255000.	8980.	56.0	0.015	157.0	1.000
			0.50	259000.	15840.	56.0	0.015	184.0	1.000
			0.43	266000.				184.0	1.000
16	17	3	BR16--POUGHKEEPSIE TO CLINTON POINT						
			0.43	266000.	13730.	56.0	0.015	177.0	1.000
			0.36	271000.	15840.	56.0	0.015	183.0	1.000
			0.30	276000.				183.0	1.000
17	18	4	BR17--CLINTON POINT TO CHELSEA PUMP STN						
			0.30	276000.	6864.	56.0	0.017	180.0	1.000
			0.25	278500.	6864.	56.0	0.017	180.0	1.000
			0.22	280000.	7920.	56.0	0.017	197.0	1.000
			0.16	282000.				197.0	1.000

Appendix II. (continued) Initial condition card input for Hudson River branches between Green Island and Hastings-on-Hudson for May 9-10, 1990

Source node	Outlet node	No. of cross sections	Stage (ft)	Discharge (cubic ft per second)	Segment length (ft)	Water temperature (˚F)	Flow resistance coefficient (*eta*)	Segment orientation[1]	Momentum coefficient
18	19	3	BR18--CHELSEA PUMP STN TO BEACON						
			0.16	282000.	13727.	56.0	0.017	208.5	1.000
			0.10	285000.	12144.	56.0	0.017	186.0	1.000
			0.02	287000.				186.0	1.000
19	20	3	BR19--BEACON TO POLLEPEL ISLAND						
			0.02	287000.	11615.	56.0	0.017	180.0	1.000
			-0.06	289000.	8000.	56.0	0.017	180.0	1.000
			-0.12	291000.				180.0	1.000
20	21	2	BR20--POLLEPEL ISLAND TO BREAKNECK POINT						
			-0.12	291000.	6864.	56.0	0.017	148.0	1.000
			-0.16	291500.				148.0	1.000
21	22	3	BR21--BREAKNECK POINT TO COLD SPRING						
			-0.16	291500.	6325.	56.0	0.017	152.0	1.000
			-0.20	292000.	5808.	56.0	0.017	155.0	1.000
			-0.25	293000.				155.0	1.000
22	23	6	BR22--COLD SPRING TO WEST POINT SOUTH DOCK						
			-0.25	293000.	1600.	56.0	0.017	180.0	1.000
			-0.26	293000.	3550.	56.0	0.017	159.0	1.000
			-0.29	293500.	1900.	56.0	0.017	106.0	1.000
			-0.31	293500.	2200.	56.0	0.017	170.0	1.000
			-0.33	294000.	3000.	56.0	0.017	200.5	1.000
			-0.34	294000.				200.5	1.000

Appendix II. (continued) Initial condition card input for Hudson River branches between Green Island and Hastings-on-Hudson for May 9-10, 1990

Source node	Outlet node	No. of cross sections	Stage (ft)	Discharge (cubic ft per second)	Segment length (ft)	Water temperature (°F)	Flow resistance coefficient (*eta*)	Segment orientation[1]	Momentum coefficient
23	24	6	BR23--WEST POINT SOUTH DOCK TO INDIAN POINT						
			-0.34	294000.	12144.	56.0	0.015	190.0	1.000
			-0.36	295000.	14784.	56.0	0.015	209.0	1.000
			-0.38	295500.	11088.	56.0	0.015	139.5	1.000
			-0.40	296000.	5808.	56.0	0.015	163.0	1.000
			-0.43	296000.	10032.	56.0	0.015	215.0	1.000
			-0.45	295000.				215.0	1.000
24	25	4	BR24--INDIAN POINT TO BOWLINE POINT						
			-0.45	295000.	6864.	56.0	0.015	158.5	1.000
			-0.46	294500.	6864.	56.0	0.015	156.0	1.000
			-0.49	294000.	10032.	56.0	0.015	151.0	1.000
			-0.53	293000.				151.0	1.000
25	26	3	BR25--BOWLINE POINT TO TELLERS POINT						
			-0.53	293000.	10032.	56.0	0.0185	155.5	1.000
			-0.55	292000.	6336.	56.0	0.0185	149.0	1.000
			-0.57	291000.				149.0	1.000
26	27	7	BR26--TELLERS POINT TO HASTINGS-ON-HUDSON						
			-0.57	291000.	8448.	56.0	0.0185	160.5	1.000
			-0.60	290000.	13200.	56.0	0.0185	183.0	1.000
			-0.65	287000.	12672.	56.0	0.0185	180.0	1.000
			-0.70	283000.	12672.	56.0	0.0185	180.0	1.000
			-0.74	279000.	11616.	56.0	0.0185	177.0	1.000
			-0.79	273000.	6426.	56.0	0.0185	180.0	1.000
			-0.82	268000.				180.0	1.000

[1] Segment orientation measured clockwise to positive axis, in degrees from true north.