Citation: Weiss, L.A., Schaffranek, R.W., and de Vries, M.P., 1994, Flow and chloride transport in the tidal Hudson River, New York, in Hydraulic Engineering ‘94: Proceedings of the American Society of Civil Engineers, v. 2, p. 1300-1305.

FLOW AND CHLORIDE TRANSPORT IN THE TIDAL HUDSON RIVER, NY

Lawrence A. Weiss[1], Member, ASCE, Raymond W. Schaffranek[2],Member, ASCE, and M. Peter deVries[3]

ABSTRACT

A one-dimensional dynamic-flow model and a one-dimensional solute-transport model were used to evaluate the effects of hypothetical public-supply water withdrawals on saltwater intrusion in a 133-mile reach of the tidal Hudson River between Green Island dam, near Troy, N.Y., and Hastings-on-Hudson, N.Y. Regression techniques were used in analyses of current and extreme historical conditions, and numerical models were used to investigate the effect of various water withdrawals. Of four withdrawal scenarios investigated, simulations of a 27-day period during which discharges at Green Island dam averaged 7,090 ft^3/s indicate that increasing the present Chelsea pumping-station withdrawal rate of 100 Mgal/d (million gallons per day) to 300 Mgal/d would have the least effect on upstream saltwater movement. A 90-day simulation, during which discharges at Green Island dam averaged 25,200 ft^3/s, indicates that withdrawals of 1,940 Mgal/d at Chelsea would not measurably increase chloride concentrations at Chelsea under normal tidal and meteorological conditions, but withdrawals of twice that rate (3,880 Mgal/d) could increase the chloride concentration at Chelsea to 250 mg/L.

INTRODUCTION

New York City's water-supply system serves over 9 million people in the City and five nearby counties; several upstate communities also could use the system during an emergency. 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.

During 1989-91, the U. S. Geological Survey (USGS), in cooperation with the New York City Department of Environmental Protection, the New York State Department of Environmental Conservation, and the Hudson Valley Regional Council, studied the hydrodynamic and solute-transport properties of the 133-mi reach of the tidal Hudson River between Green Island dam near Troy and Hastings-on-Hudson, N.Y. Tidal flow was simulated with the USGS Branched-Network Dynamic Flow model (BRANCH) (Schaffranek and others 1981; Schaffranek 1987). Chloride transport was simulated with the BRANCH-computed flows in the USGS Branched Lagrangian Transport Model (BLTM) (Jobson and Schoellhamer 1987). The effect of combined hypothetical withdrawals at varied rates at (1) Chelsea, (2) Kingston and Chelsea, (3) Chelsea and Newburgh,

1. Hydrologist, U.S. Geological Survey, Abraham A. Ribicoff Fed. Bldg., 450 Main St., Room 525, Hartford, CT 06103.
2. Hydrologist, U.S. Geological Survey, National Center, MS 430, Reston, VA 22092.
3. Hydrologist, U.S. Geological Survey, 425 Jordan Rd. Troy, New York 12180.

and (4) Kingston and Newburgh, on upstream saltwater movement were simulated. Regression techniques were used to relate the locations of cross-sectional mean chloride concentrations of 100- and 250-mg/L under non-withdrawal conditions to daily mean values of specific conductance measured at West Point. An empirical relation for locating the 100 mg/L cross-sectional mean chloride concentration was also obtained by correlating chloride concentrations with tides at West Point and daily mean inflows at Green Island dam plus five intervening tributaries.

This paper gives an overview of the study reach and a summary of the model implementations, regression analyses, and flow withdrawal and augmentation simulations.

MODEL REACH AND FLOW CHARACTERISTICS

The 153.7-mi tidal reach of the Hudson River between Green Island dam, near Troy, and the Battery, in New York City, at river mile (RM) zero (fig.1), is a drowned-river estuary with a mean bed slope of 0.0002 ft/ft; mean tidal range is about 5.5 ft. This study focused mainly on the 77-mi reach from Turkey Point near Saugerties (RM 98.5) to Hastings-on-Hudson (RM 21.5) (fig.1), which encompasses the transition zone between fresh and salt water. Under normal inflow and tidal conditions, this zone extends about 46 mi from New Hamburg (RM 67.7) to Hastings-on-Hudson. Chloride concentrations are typically less than 25 mg/L at Clinton Point, near New Hamburg, and greater than 3,000 mg/L at Hastings-on-Hudson, but they can vary greatly within the cross section and reach as well as through time. During summer, measured tidal flow ranges from about 20,000 ft^3/s at Albany to 400,000 ft^3/s at Tellers Point near Ossining (Stedfast 1982). Freshwater inflow to the tidal river is primarily from the upper river basin and is measured at the dam at Green Island. Inflows from six tributaries (Moordener Kill, Esopus Creek, Rondout Creek, Wallkill River, Wappinger Creek, and Croton River) to the tidal river are also continuously measured (fig.1).

BRANCH AND BLTM IMPLEMENTATION

The BRANCH model uses a four-point, nonlinear, implicit finite-difference approximation of the unsteady flow equations. The unsteady flow equations account for nonuniform velocity distribution in the cross section by the Boussinesq coefficient, flow conveyance and storage separation, lateral flows, pressure differentials that result from density variations, and wind stress as a forcing function. 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.

For purposes of BRANCH model implementation, the Hudson River was divided into 26 subreaches (branches) between Green Island dam and Hastings-on-Hudson. Additional branches were used for five major tributaries. Boundary-value data were supplied at Green Island dam, Hastings-on-Hudson, and at the tributaries. The model was calibrated and verified to 19 tidal-cycle discharge measurements made at 11 locations with conventional and acoustic Doppler current-profiler methods. Successive ebb- and flood-flow volumes were measured and compared with computed volumes; differences ranged from –13.8 to +22.3 percent.

The BLTM was used to simulate chloride transport in the 61-mi reach from Turkey Point to Bowline Point at Haverstraw (RM 37.5) 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). Measured chloride concentrations at Haverstraw were used to drive the BLTM simulations, and data collected at West Point

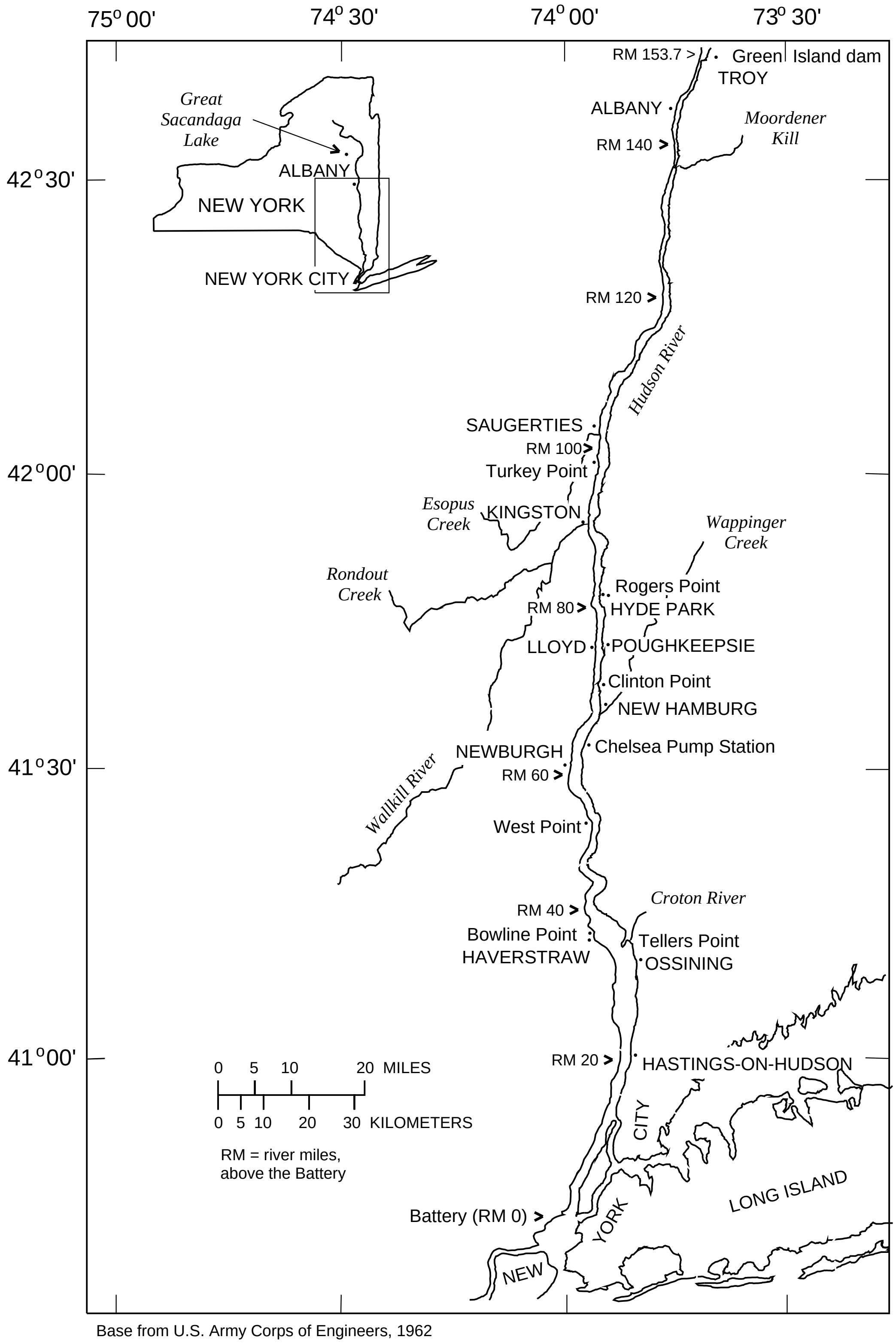

Figure 1. Tidal Hudson River study area.

were used for calibration and verification. Mean bias in simulated chloride concentration for the April-June 1990 data (observed range of 12 to 201 mg/L; 30 mg/L root mean square error (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. Because a chloride concentration of 100 mg/L was not observed at Clinton Point in 1990, solute transport between West Point and Poughkeepsie was evaluated using data from August 1991. The BLTM then was used to simulate chloride concentrations at Chelsea 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 and Clinton Point for model analysis. Mean biases in BLTM-simulated daily mean chloride concentrations for August 1991 were –38 mg/L at Chelsea (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).

REGRESSION ANALYSES

Regression techniques were used to derive equations to compute chloride concentrations at Chelsea and Clinton Point from specific conductance values at West Point, for use in calculating the locations of the 100- and 250-mg/L chloride concentrations from specific conductance values at West Point, and to locate the 100-mg/L chloride concentration from tide levels at West Point and inflows from Green Island dam plus five tributaries.

Relation of chloride concentrations at West Point to those at Chelsea and Clinton Point

Regression equations relating daily mean chloride concentrations at West Point, in mg/L (x), to those at Chelsea and Clinton Point (y) were determined to be $y = (x^{1.69}/598) - 150$ and $y = (x^{1.829}/2{,}838) - 150$, respectively. The coefficients of determination for Chelsea and Clinton Point equations were 0.897 and 0.943, respectively, and the standard errors of estimates were ±9.6 and ±7.7 percent, respectively.

Relation of tide levels and inflows to the 100-mg/L chloride-concentration location

Physical factors that affect chloride transport are stream geometry, freshwater inflows, ocean tides and the relation of their size to lunar cycles, and wind velocity. Antecedent conditions must also be considered in any attempt to develop longitudinal concentration profiles. Chloride concentrations can be approximated from freshwater inflows and maximum tidal effect for conditions of constant channel geometry, wind velocity less than 5 mi/h, and initial water density of 1.939 slug/ft^3 (fresh water). Water levels at West Point were used to evaluate tidal effect, and the initial water density for the 17 observations of the 100-mg/L chloride-concentration location 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 dam 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 of West Point at high slack tide, in RM, is: $ClL = (877T^{0.38})/(F^{0.34})$, where T is tide level, in ft above mean sea level, and F is inflow, in ft^3/s. The coefficient of determination was 0.757, and the standard errors of estimates were +5.5 and –6.6 percent. This equation has a mean error of 2.4 mi and a RMSE of 5.9 mi.

Relation of specific conductances at West Point to chloride-concentration locations

Equations used to estimate the locations of the 100- and 250-mg/L chloride concentrations for the Hudson River upstream of West Point were developed from daily mean specific conductance values at West Point. In these equations, *ClL* is chloride-concentration location at high slack tide, in river miles, and *SpC* is daily mean specific conductance at West Point, in

μS/cm (r^2 = coefficient of determination and Sy.x = standard error of estimate). Regression data used to develop the equations consisted of 21 observations in which specific conductance ranged from 169 to 7,210 μS/cm, and the 100-mg/L chloride-concentration locations ranged from RM 36.4 to 75.3:

Location of 100-mg/L chloride concentration:

$$ClL = -4{,}840 + 237.2\ln(SpC) + 27{,}193/\ln(SpC) - 21{,}347/SpC^{0.5}$$

r^2 = 0.986, Sy.x = 1.45 miles, RMSE = 1.5 miles

Location of 250-mg/L chloride concentration:

$$ClL = -9{,}035 + 422.0\ln(SpC) + 52{,}140/\ln(SpC) - 43{,}392/SpC^{0.5}$$

r^2 = 0.994, Sy.x = 0.91 miles, RMSE = 0.85 miles

Recent applications

Subsequent tests of the West Point specific conductance regression equations on days of high chloride concentrations at West Point in July and August 1993 verified the 100-mg/L chloride-concentration location within 1.8 and 0.2 miles, respectively. On July 21, 1993, when the daily mean specific conductance at West Point was 6,590 μS/cm, the 100-mg/L chloride concentration was observed at RM 73.5 and was computed to be at RM 75.3. On August 19, 1993, the daily mean specific conductance at West Point was 6,380 μS/cm, and the observed and computed 100-mg/L chloride concentrations were at RM 74.5 and 74.7, respectively. The 100-mg/L equation indicates that, for the 100-mg/L chloride concentration to reach the Poughkeepsie water-treatment plant (RM 77.2) would require a daily mean specific conductance of at least 7,350 μS/cm at West Point, which is equivalent to a 643 mg/L daily mean chloride concentration at Chelsea.

Historical Application

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 about 35 to 80 years (Gravlee and others 1991). Another regression equation, relating chloride concentration at Poughkeepsie to specific conductance at West Point, indicates that, on this day, the specific conductance at West Point would have been 10,780 μS/cm. This value, applied to the West Point specific conductance equations, places the 100- and 250-mg/L chloride concentrations at RM 85.5 and 80.8, respectively. (Note: Use of these equations is for historical reference only and must be interpreted with caution since the specific conductance is beyond the range of values used to develop the equations.) Applying the 5-day mean inflow (F) of 2,920 ft^3/s upstream of West Point and the 5-day tide level (T) 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 the tide and inflow regression equation yielded a 100-mg/L chloride concentration at RM 88.3, which is 2.8 mi upstream of the location computed from the 100-mg/L West Point specific conductance equation.

WITHDRAWAL AND FLOW-AUGMENTATION SIMULATIONS

Simulated withdrawals of 300 Mgal/d at Chelsea, 100 Mgal/d at Chelsea and 200 Mgal/d at either Kingston or Newburgh, and 100 Mgal/d at Kingston and 200 Mgal/d at Newburgh were made with BRANCH to evaluate the traveltime of a nondispersive particle and the BLTM to evaluate the effects of withdrawals on upstream movement of a dispersive particle. Results for nondispersive particles injected between Green Island and Tellers Point indicate that, of the four scenarios evaluated for the period of moderate flow (July 18 to August 13, 1990), during which discharges at Green Island dam averaged 7,090 ft^3/s, increasing the Chelsea pumping station withdrawal rate from 100 Mgal/d to 300 Mgal/d would have the smallest effect on saltwater movement, whereas withdrawing 200 Mgal/d at Kingston while also withdrawing 100 Mgal/d at either Chelsea or Newburgh would have the greatest effect.

Simulations of increased river flows at Green Island dam were made to evaluate the effect of flow augmentation on the upstream movement of salt water. Results of a simulation for a period of low flow (August 9-31, 1991), show that hypothetical flow increases of 1,000 ft^3/s and 5,000 ft^3/s, when daily inflow averaged 4,400 ft^3/s at Green Island dam, could cause the 100-mg/L chloride concentration to move 0.6 and 7.2 mi downstream, respectively. Simulations of hypothetical withdrawals at Chelsea during a high-flow period (April 1 to June 30, 1990), when mean inflow at Green Island dam was 25,200 ft^3/s, indicate that a withdrawal of 1,940 Mgal/d would not measurably affect the local chloride concentration, but withdrawing at twice that rate (3,880 Mgal/d) could increase it to 250 mg/L.

SUMMARY

The feasibility of withdrawing water from the tidal Hudson River was investigated during 1989-91. Several scenarios of withdrawals at Kingston, Chelsea, and Newburgh were analyzed through dynamic-flow and solute-transport models and regression techniques.

Results of regression analyses relating chloride-concentration locations to daily mean values of specific conductance measured at West Point closely matched observed locations. The 100- and 250-mg/L chloride regressions had standard errors of estimate of 1.4 and 0.9 mi, respectively. Results of application of the 100-mg/L chloride-concentration equation to specific conductances measured at West Point in July and August 1993 matched the observed 100-mg/L chloride-concentration locations within 1.8 and 0.2 mi, respectively.

Tidal flow in the Hudson River was simulated by the USGS one-dimensional Branched-Network Dynamic Flow (BRANCH) model, and chloride transport was simulated from the computed unsteady flows generated by BRANCH in the USGS Branched Lagrangian Transport Model (BLTM). After model calibration and verification, simulations were run to evaluate selected withdrawal scenarios. Results indicate that, of the scenarios evaluated, the one that would cause the least upstream saltwater movement would entail increasing the present withdrawal rate of 100 Mgal/d at Chelsea pumping station to 300 Mgal/d.

REFERENCES

Gravlee, G.C.Jr., Lumia, R., and Wolcott, S.W. (1991). Hydrologic Events and Floods and Droughts, in Paulson, R.W., ed., National Water Summary 1988-89: U.S. Geological Survey *Water Supply Paper 2375*, 415-423.

Jobson, H.E., and Schoellhamer, D.H. (1987). Users Manual for a Branched Lagrangian Transport Model: U.S. Geological Survey *Water-Resources Investigations Report 87-4163*.

New York City (1992). Mayor's Intergovernmental Task Force on New York City Water Supply Needs: The Future of the New York City Water Supply System: *Final Report, 92-6003*.

New York State Department of Environmental Conservation and New York City Department of Environmental Protection (1989). Study of Water Demands on New York City Water Supply System: Final Report, prepared by Hazen and Sawyer, P.C., Eng.

Schaffranek, R.W., Baltzer, R.A., and Goldberg, D.E. (1981). A Model for Simulation of Flow in Singular and Interconnected Channels: U.S. Geological Survey *Techniques of Water-Resources Investigations, Book 7*, *Chapter C3*.

Schaffranek, R.W. (1987). Flow Model for Open-Channel Reach or Network: U.S. Geological Survey *Professional Paper 1384*.

Stedfast, D.A. (1982). Flow Model of the Hudson River Estuary from Albany to New Hamburg, New York: U.S. Geological Survey *Water-Resources Investigations Report 81-55*.

Authors note: Several equations presented in this paper have been updated to incorporate additional data collected since the date of publication. Inquiries may be sent to U.S. Geological Survey, 425 Jordan Rd. Troy, NY 12180 or internet mail to pdevries@usgs.gov.