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MODELING FLOW AND FLOOD-PLAIN STORAGE IN A TIDALLY AFFECTED RIVER

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ABSTRACT

A one-dimensional, unsteady-flow model was calibrated, validated, and tested for a 30.4-mile reach of the tidally affected Roanoke River, North Carolina. The model includes a storage reservoir to represent the two-dimensional processes associated with flood-plain storage and release in the one-dimensional flow model. Simulated and measured water levels differed by less than 0.5 foot, and the average absolute difference between simulated and measured flows was 7 percent.

INTRODUCTION

The Roanoke River drainage basin includes 9,666 square miles (mi^2) in southern Virginia and northern North Carolina. The flow from the Roanoke River into Albemarle Sound is estimated to average about 8,900 cubic feet per second (ft^3/s) (Giese and others, 1985).

Conditions in Albemarle Sound affect flows in the Roanoke River approximately 60 miles upstream from the mouth of the river (Giese and others, 1985). Consequently, standard stream-gaging techniques, which are based on a unique and fairly stable relation between stage and discharge at a selected site, cannot be used to determine flow rates in the lower 60 miles of the Roanoke River. Flow models, however, may be used to compute continuous records of discharge at sites where standard techniques are not applicable.

This paper documents development and testing of a one-dimensional, unsteady-flow model for computing discharge in a tidally affected reach of the Roanoke River. A general description of the study reach is followed by a summary of data-collection, discussion of the study reach schematization, and results of model calibration, including a novel approach for representing two-dimensional processes associated with flood-plain storage in a one-dimensional flow model. The investigation was conducted by the U.S. Geological Survey, in cooperation with the Division of Water Resources of the North Carolina Department of Environment, Health, and Natural Resources.

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STUDY AREA AND DATA COLLECTION

The study area is a 30.4-mile reach of the Roanoke River between river mile (RM) 67.0 (NC 42-11 bridge) and RM 36.6 (US 13-17 bridge) (fig. 1). Flows in the study reach are regulated by releases from a reservoir located on the mainstem of the Roanoke at RM 137.0 The study area includes Conoho Creek and the head of Conine Creek, through which some water bypasses a segment of the Roanoke. Conoho Creek, which flows into the Roanoke at RM 37.9, is the largest tributary in the study reach, having a drainage area of 120 mi^2. The Conoho Creek basin represents 47 percent of the 257-mi^2 sub-basin that drains directly to the study reach. Total drainage area of the Roanoke basin at RM 67.0 is 8,813 mi^2.

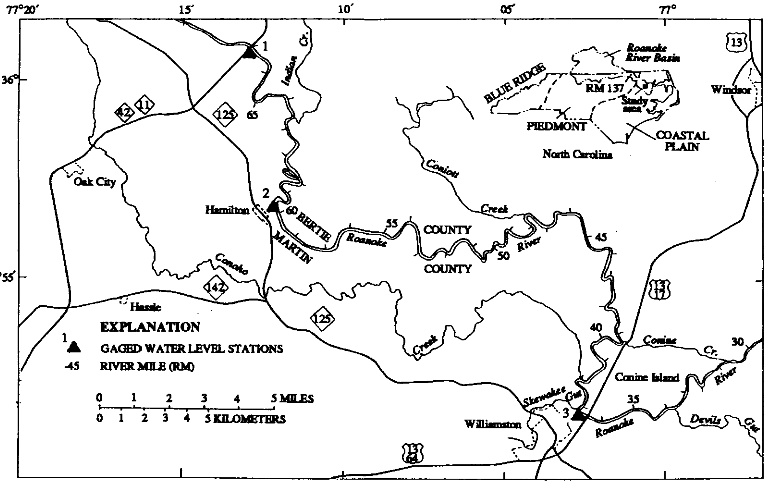

Figure 1.--Location of study area.

The Roanoke River is tributary to Albemarle Sound, which is an oligohaline lagoonal estuary having a surface area of 480 mi^2 and no direct connection to the ocean. Water-level variations at the mouth of the Roanoke River are well correlated with tides at the eastern end of Albemarle Sound. The tidal range is about 0.5 foot (ft) at the eastern end of Albemarle Sound and is about the same at the mouth of the river, except when river flows are greater than about 10,000 ft^3/s.

The study reach is located in the Coastal Plain physiographic province of North Carolina. Streams which drain to the study reach are relatively small and have low gradients. Some of the land that drains to the study reach is artificially drained through ditches and canals to facilitate development. The bottomland hardwood forest along the Roanoke River is considered to be one of the largest intact, least-disturbed ecosystems of its kind in the eastern United States.

Climate in the region is moderately mild and humid. The annual mean temperature at Williamston is about 60 °F, mean annual precipitation is about 50 inches, and evapotranspiration averages about 34 inches per year (in/yr) (Wilder and others, 1978). On the average, about 30 percent of the total precipitation that occurs in the study area reaches streams through either surface runoff or ground-water discharge (Wilder and others, 1978). According to Krug and others (1990), the long-term average annual runoff in the vicinity of the study reach is about 14 inches, or 1.03 cubic feet per second per square mile ($[ft^3/s]/mi^2$).

Data collection for the investigation included (1) hourly measurements of water level, (2) discrete measurements of discharge, and (3) measurements of channel geometry and flood-plain topography. Three water-level recorders are located in the study reach, with one recorder at the upstream boundary, one recorder at RM 59.2, and one recorder at the downstream boundary. A total of 33 discharge measurements were made in the study reach. Most of the data for this study were collected in 1990 and 1991.

TIDAL RIVER FLOW MODEL

Model development consisted of calibration, validation, and sensitivity testing. Model calibration is accomplished by adjusting model parameters until model results agree with observations (Ditmars and others, 1987). The model is considered to be validated if results agree with observations distinct from those used for calibration without further adjustment of model parameters (Ditmars and others, 1987). The model is assumed to be valid over the range of conditions used in the calibration and validation process. Sensitivity testing is the determination of the effects on simulation results of small changes in model parameters or input data.

Model Description: A one-dimensional, unsteady-flow model (Schaffranek and others, 1981) was used to compute flows in the study reach. The flow model is based on the cross-sectionally averaged (or one-dimensional), nonlinear momentum and continuity equations for unsteady flow in prismatic channels. The governing equations include the assumptions that (1) the water density is essentially homogeneous throughout the study reach (2) hydrostatic pressure distribution prevails, (3) the flow is subcritical, and (4) energy losses are accounted for using a resistance coefficient analogous to Mannings $\underline{n}$. Because the governing equations are cross-sectionally averaged, bidirectional flow at a cross section (either across the channel or in the vertical plane) cannot be simulated by the model. Upstream and downstream flow at different cross sections within the study reach, however, can be simulated. The governing equations are solved for the two unknowns--water level and flow--using a weighted, four-point, implicit finite-difference scheme.

The study reach must be described as a series of branches, segments, junctions, and cross sections or computational points. Locations at which two or more channels join or where local inflows must be accommodated are internal junctions. Channel reaches between junctions are called branches, which may be further subdivided into segments. Locations at which a single branch is defined are external junctions. User-supplied boundary conditions (time sequence of water level or discharge) are required at external junctions; inflows or losses within the study reach are also required as boundary conditions. Selection of segments, where model results are provided, is based on variability in cross-sectional geometry and computational considerations.

Model Schematization: The 30.4-mile study reach is represented by 10 branches and 38 cross sections. Nine branches and 32 cross sections were used to represent the mainstem of the river. Also included in the model is Conoho Creek, which was represented by one branch and six cross sections. Flow lost from the Roanoke River through Conine Creek is not included in the model. Daily mean flow per square mile at three nearby index stations was used to estimate local inflow to the Roanoke from the study reach sub-basin.

The model was constructed to simulate water levels which are below the top of bank. The natural levee along the Roanoke River is breached, however, by numerous drainage canals and a few creeks, especially near the lower end of the study reach. These channels provide conduits for flow to move out of the river and into the flood plain during high water levels. As the water level falls, water slowly drains back into the river. This process, which is different from water spilling over the top of the bank during high flows, has been accommodated in the model.

Preliminary model results indicated that storage and release of water from the Roanoke River flood plain were not being simulated properly. This problem was solved by treating a part of the Conoho Creek drainage basin as a storage reservoir. This storage reservoir was connected to the Roanoke River by a relatively small channel so that the reservoir would fill and drain slowly, thus mimicking flood plain processes. The storage reservoir, which has a surface area of 29 mi^2 at a water surface elevation of 8 ft, is effective at water levels greater than 4 ft.

Calibration and Validation: Model calibration is required to adapt the general branch-network flow model to the specific application in the study reach. A computational time step of 15 minutes gave the most satisfactory compromise between computational cost and model accuracy. Fifteen-minute interval input data from the upstream and downstream boundary water-level recorders were linearly interpolated from hourly observations.

Minor adjustments to cross-sectional area at some of the measured cross sections were required during calibration. Adjustments were generally at the higher water levels, where direct measurements of cross-sectional geometry were more difficult.

Within the calibrated model, the resistance coefficient is specified as a function of water level at each cross section. Resistance coefficients range from 0.034 to 0.048, with the higher values generally applying to the lower water levels.

The momentum coefficient corrects for effects of nonuniform velocity distributions on flows. A value of 1.06, which is typical for turbulent flows in natural channels, was used.

The model requires the specification of two numerical-solution weighting factors--chi and theta (Schaffranek and others, 1981). A value of 0.75 was used for chi, which controls phase lag in the solution. Theta, which affects numerical stability, was also set to 0.75. These values are well within the range used by others.

Model calibration and validation were conducted for three sets of arbitrarily selected sets of water-level conditions to test model performance at high, mid-range, and low water levels. Simulated water levels were compared with measured values at RM 59.2. Simulated and measured water levels typically differed by less than 0.5 ft, and the difference between measured and simulated water depth was generally less than 5 percent.

Twenty-four of the 33 flow measurements were used for model calibration. The maximum difference between measured and simulated flows was 16 percent, and the average absolute difference for all 24 values was 7 percent. Because actual flow measurements are generally considered to have an accuracy of no better than 5 percent, these flow simulations were considered to be in reasonably good agreement with measured flows.

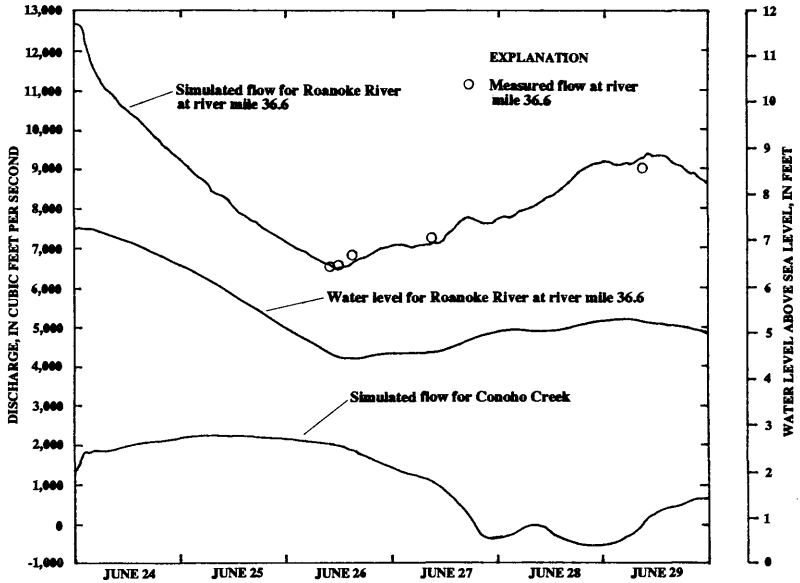

Figure 2.--Simulated flow, measured flow, and water level for the Roanoke River at river mile 36.6 and simulated flow for Conoho Creek, June 24-29, 1990.

Simulated and measured flows at RM 36.6, the downstream boundary, are shown in figure 2 for a high-flow condition. Simulated storage and release from the Conoho Creek storage reservoir is also shown in the figure. Early in the simulation, the falling water levels at the downstream boundary result in the release of water from storage. The amount of water released from storage (shown by positive flow for Conoho Creek) is a relatively high proportion of the total flow. Water begins flowing back into storage several hours after the minimum river flow is reached.

Model validation results were similar to those obtained during calibration. The maximum difference between simulated and measured flows over the range of water levels was 13 percent, and the average absolute error was 7 percent.

Sensitivity Analysis: The model was somewhat unstable at a computational time step of 30 minutes, but no difference was observed between results of simulations made using 5-minute and 15-minute time steps. Simulated water levels were insensitive to changes in the resistance coefficient of up to 10 percent (increase or decrease). The magnitude and timing of simulated flows were affected by changes in the resistance coefficient, but the effects were small. Results were also insensitive to the values of chi and theta at the 15-minute computational time step.

SUMMARY

A one-dimensional, unsteady-flow model was calibrated, validated, and tested for a 30.4-mile reach of the tidally affected Roanoke River, North Carolina. The model includes a storage reservoir to simulate the slow storage and release of water from the flood plain along the river. Simulated and measured water levels differed by less than 0.5 ft, and the average absolute difference between simulated and measured flows was 7 percent. The model was relatively insensitive to changes in resistance coefficient and numerical weighting factors, but was unstable at some flows with a time step of 30 minutes.

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