

HYDROLOGIC MODELING OF THE LOWER ALTAMAHA RIVER BASIN

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Abstract. An integrated hydrologic model is developed for the lower Altamaha river basin to facilitate the overall understanding of the system and to provide necessary information for future water quality modeling and management efforts. The numerical model integrates all major surface and subsurface flow pathways and implements the first principles in a multi-dimensional framework. In its current state, the model includes (i) a one-dimensional river/stream flow component and (ii) a two-dimensional groundwater flow component. These components are linked along the river-bottom interface by using a simultaneous coupling procedure. Simulations performed with this physically-based coupled model reveal the response characteristics of the lower Altamaha basin to various hydrological inputs.

INTRODUCTION

Use and development of coupled hydrologic models are one of the active research areas in the field of hydrological modeling. Several researchers have worked on coupled models of surface and subsurface flows in an attempt to better simulate the behavior of water movement in a watershed (Akan and Yen, 1981; Swain and Wexler, 1991; Van der Kwaak and Loague, 2001 and Morita and Yen, 2002). Although most of these models are fairly complex in simulating the overall water movement in a watershed, they are limited in applications to large watersheds. In this study, a coupled surface-subsurface model is developed as a part of an integrated watershed modeling system that can accurately simulate the major hydrologic pathways but yet can be applicable to large basins such as the Altamaha.

MATHEMATICAL BACKGROUND

The proposed model is a combination of a one-dimensional channel flow model and a two-dimensional saturated groundwater flow model. The channel flow

model is based on the dynamic wave form of the St. Venant equations modified for natural waterways (Fread, 1993):

$$\frac{\partial s_c (A + A_o)}{\partial t} + \frac{\partial Q}{\partial x} - q_L = 0 \quad (1)$$

$$\frac{\partial s_m Q}{\partial t} + \frac{\partial (bQ^2 / A)}{\partial x} + gA \left(\frac{\partial h_r}{\partial x} + S_f + S_e \right) + L = 0 \quad (2)$$

where s_c and s_m are sinuosity factors for continuity and momentum equations, A is the active cross sectional area of flow, A_o is the inactive (off-channel storage) cross sectional area, Q is the discharge, t is the time, x is the longitudinal distance along the channel/flood plain, q_L is the lateral inflow/outflow per channel length that provides the link with the groundwater flow model (positive for inflow and negative for outflow), b is the momentum coefficient for velocity distribution, g is the gravitational acceleration, h_r is the water surface elevation in the channel (i.e., stage), L is the momentum flux due to lateral seepage inflow/outflow, S_f and S_e are channel/flood plain boundary friction slope and contraction/expansion slope, respectively. The momentum flux due to seepage inflow/outflow, channel/flood plain boundary friction slope and contraction/expansion slope are evaluated as:

$$L = \begin{cases} 0 & \text{for inflow} \\ -\frac{Qq_L}{2A} & \text{for outflow} \end{cases} \quad (3)$$

$$S_e = \frac{K_{ec} \Delta (Q/A)^2}{2g\Delta x} \quad (4)$$

$$S_f = \frac{n_c^2 |Q| Q}{c_1^2 A^2 R_h^{4/3}} = \frac{|Q| Q}{K^2} \quad (5)$$

where K_{ec} is the expansion/contraction coefficient, Δx is the reach length, c_1 is the unit system dependent

APPLICATION

constant, n_c is the Manning's roughness coefficient, K is the flow conveyance factor and R_h is the hydraulic radius. R_h is defined as the ratio of cross-section area to wetted perimeter but can be approximated as the ratio of cross-sectional area to top width for large rivers. The momentum influx due to seepage inflow is assumed to be negligible and is not considered in the model. The saturated groundwater flow model is based on the vertically-averaged mass conservation equation of groundwater flow (Aral, 1990):

$$\frac{\partial}{\partial x} \left[(h_g - z_b) K_x \frac{\partial h_g}{\partial x} \right] + \frac{\partial}{\partial y} \left[(h_g - z_b) K_y \frac{\partial h_g}{\partial y} \right] + \sum_{k=1}^{n_w} Q_{w_k} + I = S_y \frac{\partial h_g}{\partial t} \quad (6)$$

where h_g is the vertically averaged hydraulic head, z_b is the top elevation of the bottom impervious layer, K_x and K_y are saturated hydraulic conductivities in x and y directions, respectively, Q_w is the well flow rate, n_w is the number of wells in the domain, I is the infiltration rate and S_y is the specific yield of the aquifer.

The numerical solution of channel and groundwater flow models is done by a weighted four-point finite difference scheme and a Galerkin finite element method, respectively. The details of these solution procedures can be found in Aral (1990) and Fread (1993). The coupling of the two models is provided via lateral inflow/outflow. The head-dependent lateral inflow/outflow term appears as a source/sink term in the channel flow model and a boundary condition term in the groundwater flow model, and can be written as:

$$q_L = \begin{cases} -K_r w_r \frac{h_r - h_g}{m_r} & h_g > (z_r - m_r) \\ -K_r w_r \frac{h_r - (z_r - m_r)}{m_r} & h_g \leq (z_r - m_r) \end{cases} \quad (7)$$

where K_r is the river bottom sediment conductivity, m_r is the river bed sediment thickness, w_r is the wetted perimeter of the river bed and z_r is the river bottom elevation. Commonly, coupled systems such as this model are solved using iterative and non-iterative solution techniques (Akan and Yen, 1981; Van der Kwaak and Loague, 2001; Morita and Yen, 2002). In this study, however, a new more-efficient simultaneous solution algorithm proposed by Gunduz and Aral (2003) is used to solve the coupled system within a single matrix structure.

The proposed model was applied to the Altamaha River basin in southern Georgia. The modeling domain included the Altamaha River and its major tributaries (i.e., Ocmulgee, Oconee and Ohoopsee rivers) and covered the drainage area bounded by the USGS stream gaging stations at Dublin, Lumber City, Reidsville and Doctortown. This area is discretized by 16,535 nodal points and 16,168 quadrilateral finite elements in the groundwater flow zone and 829 nodal points in the channel flow zone. The average element side length along the river sections varied from 150 m to 400 m and about 1000 m elsewhere (Figure 1).

An unconfined surficial aquifer overlying the Upper Floridian aquifer is considered to be present in the entire area, with an average thickness of about 40 m. The aquifer consists primarily of unconsolidated, well sorted sand and silt soils. The STATSGO database of USDA was used as the major source of soil data (STATSGO, 1998). The saturated hydraulic conductivities of these soils are assumed to follow the statistically averaged values provided by Carsel and Parrish (1988). The Altamaha river system was modeled as a head-dependent boundary condition that creates lateral in/out flow to/from the groundwater flow domain according to the relative values of the river and groundwater heads. In addition, the natural and artificial lakes and ponds in the basin were modeled as constant-head boundary conditions.

The cross-sectional areas of computational nodes in the channel flow domain were obtained by using (i) the measurements taken at the gaging stations by USGS, (ii) the profiles of highway bridges along the river channels; and (iii) the topographic maps of the area. The Manning's roughness coefficients varied between 0.020 to 0.030 within the main channel and 0.030 to 0.070 along the floodplain. The discharge hydrographs at Dublin, Lumber City and Reidsville were used as the upstream boundary conditions of the channel model and the stage-discharge rating curve at Doctortown was used the downstream boundary condition.

The simulation period covered a two-month period starting with 09/01/1997 through 11/01/1997 with a common time step of 1 hr for both the groundwater and the channel flow domains. The total simulation time was about 1.5 days on an Intel Pentium III computer with a 1 GHz processor.

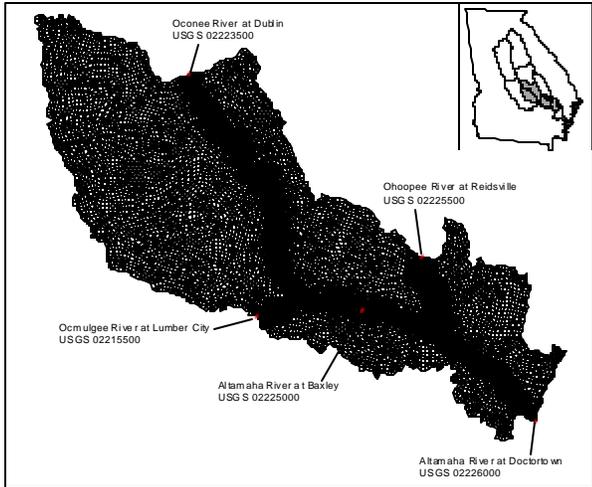


Figure 1. Numerically discretized modeling domain.

RESULTS AND DISCUSSION

The simulation results were used to analyze the hydrological response characteristics of the lower Altamaha basin. The channel flow domain results obtained at the computational points were compared with the available discharge measurements obtained at Baxley gaging station. This station is situated at the center of the domain and is believed to be a good indicator for the analysis of the simulation outputs. A comparison of model run vs. data from Baxley station is shown in Figure 2.

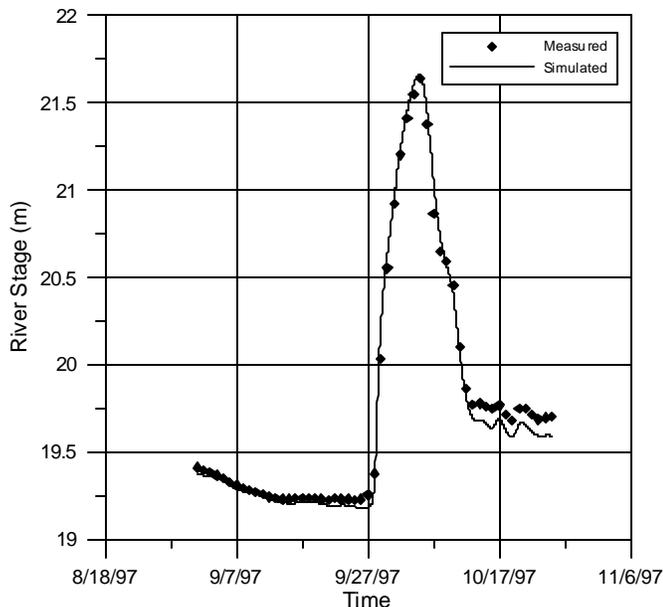


Figure 2. Measured vs. simulated river stage at Baxley.

As seen from the figure, the simulated river stages at Baxley gaging station are very close to the measured stages. The maximum deviation from the measured stages is computed to be 0.5% towards the end of the simulation period. This value is well below the accepted deviations reported in the literature (Fread, 1985). Although not presented here, the simulated discharges also follow a similar pattern and are very close to the measured values.

The groundwater head contours obtained at the end of the simulation period are shown in Figure 3. The head contours in the surficial aquifer follow the surface elevation. The groundwater head contours are consistent with the river positions within the domain. Most of the closed contours are attributed to the natural and artificial ponds and lakes that are included in the simulations as constant head boundary conditions. Along all no-flux boundaries of the domain, the groundwater contours make perfect right angles representing the absence of any flow out of these boundaries.

The interaction between the surface water and groundwater is presented in Figure 4. The groundwater heads peak due to the arrival of the flood wave. The increased flux towards the groundwater domain creates higher head values in the immediate vicinity of the river flood plain. However, due to the large nodal spacing used along the channel vicinity (about 300m) and the non-symmetric nodal positions in both banks of the river, the entire behavior of the bank-storage effect along the channel is not captured fully.

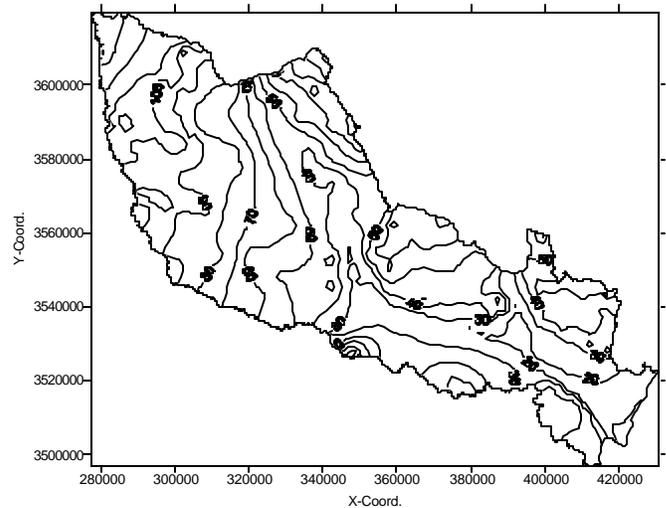


Figure 3. Simulated groundwater heads in the domain at the end of the simulation period.

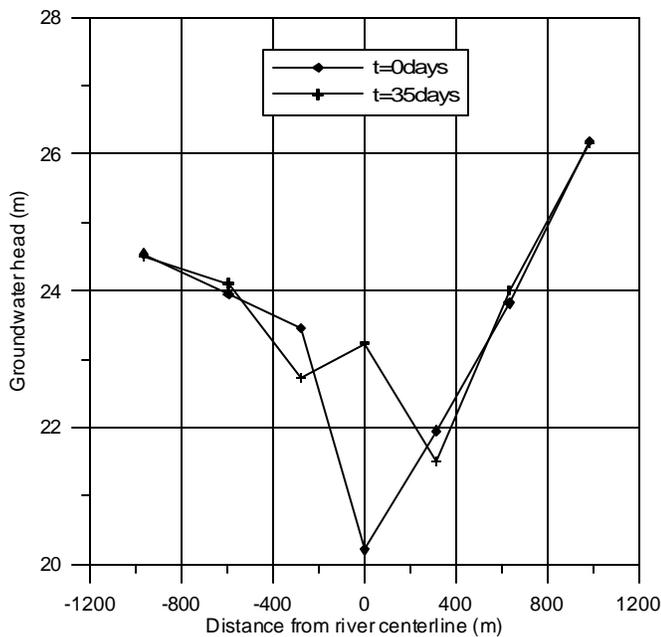


Figure 4. The interaction between the surface water and groundwater at Baxley gage site.

CONCLUSIONS AND FUTURE WORK

The hydrological characteristics of the Altamaha basin were analyzed using a coupled surface/subsurface flow model. The model links a one-dimensional channel flow model with a vertically-averaged two-dimensional groundwater flow model via the lateral seepage term. The simulation of the Altamaha basin is performed for a two month period in 1997. Simulation results obtained for the river channel stage and discharge, when compared with the field data obtained from a gaging station near Baxley, GA, indicated a good fit. When the other pieces of the modeling system are integrated to the present model, we expect this comparison to improve further. The simulation results also illustrate the interaction between groundwater flow domain and the surface water flow domain.

The model is still under development and calibration stage. The early simulations present promising results for the overall understanding of the Altamaha river basin. This coupled model will eventually be combined with an unsaturated zone model and an overland flow model to form an integrated hydrologic modeling system for the basin.

The purpose of this study is the development of the methodology for integrated large scale distributed modeling systems for watersheds. The methodology described in this paper is unique and promising. The

application of this methodology to Lower Altamaha River basin may provide a better interpretation of hydrogeologic conditions in this river basin.

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