High-Resolution Groundwater Models for the Assessment of Riparian Restoration Options and River Conveyance Efficiency

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ABSTRACT

A suite of groundwater models have been developed for the shallow riparian environment along the Rio Grande in New Mexico to support analysis of restoration options and river management strategies.[1] Five fine-mesh, three-dimensional riparian zone groundwater models (riparian models) were developed for the Rio Grande in central New Mexico spanning approximately 120 river miles. Each of the four-layer models has a uniform grid, with grid cells measuring 250 feet x 125 feet. The five models represent physical processes relevant to assessing shallow groundwater conditions, exchanges between surface water and shallow groundwater within the floodplain of the Rio Grande, and interaction between shallow and deep groundwater systems. Modeled interactions include seepage from the river, interception of shallow groundwater by drains, recharge to shallow groundwater from flooded overbank areas, and water depletions due to open water evaporation and riparian evapotranspiration, implemented using the RIP-ET package. Riparian evapotranspiration rates are variable, depending on the existing mapped vegetation classifications in the riparian zone. The models have been used to evaluate the relationship of shallow riparian groundwater conditions to variations in (a) regional groundwater conditions, (b) flood magnitude and duration, and (c) vegetation type and coverage. The simulations conducted illustrate the dynamic nature of riparian zone behavior.

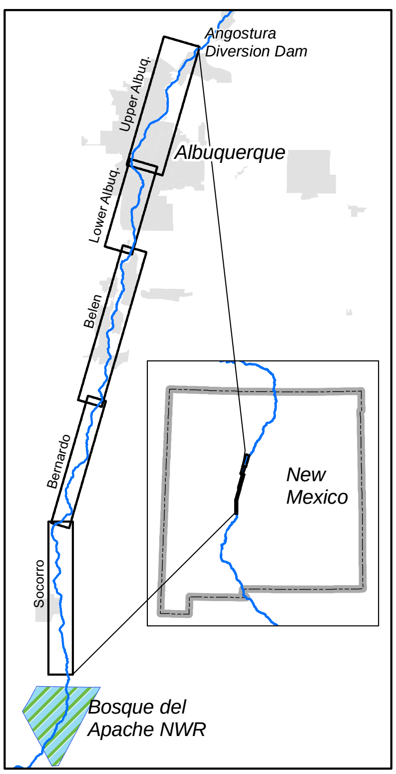

Figure 1. Study Area

INTRODUCTION

Numerous long-term projects have substantially improved our ability to understand and model hydrologic conditions along the Rio Grande, and many models have been developed as part of these studies. However, existing models do not provide the resolution needed to address some water supply and water restoration planning questions related to shallow, riparian groundwater conditions. In particular, a need was identified for models that represent fine-scale surface-water/groundwater interactions under a variety of existing and proposed management conditions, and for assessment of how differences in antecedent or regional hydrologic conditions, channel structure or vegetation type might affect surface-water/groundwater interactions. The riparian models developed in this study fill this niche, and can be applied to assess the water supply needs and sustainability of stream restoration projects under varying hydrologic or physical conditions.

The study area for this project extends along the Rio Grande from the Angostura Diversion Dam north of Albuquerque, NM, to the northern edge of the Bosque del Apache National Wildlife Refuge, a distance of approximately 120 river miles (Fig. 1). This area lies within the Middle Rio Grande region of New Mexico, defined as the reach of river valley extending from Cochiti Reservoir in the north to Elephant Butte Reservoir in the south.

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The models cover the Rio Grande corridor, riverside bosque, riverside drains, and the low-flow conveyance channel. Hydrologic inflows and outflows in this area include river leakage, riverside drain and conveyance channel gains/loss, evaporative losses from open water and bare ground, evapotranspirative losses from the riparian forest, and the movement of water to or from the regional groundwater flow system. This study examines the system under current groundwater development conditions and different flow regimes, such as low summer flows, spring runoff pulses, and average winter flows, and explores questions such as how changes in vegetation impact river flows.

METHODS FOR RIPARIAN MODEL DEVELOPMENT

The riparian groundwater models were developed in MODFLOW 2000 (Harbaugh et al., 2000). A very fine mesh (with cell size of 250 x 125 feet) is used for the models to allow for detailed assessment of riparian groundwater conditions and surface water-groundwater exchanges. The active model cells were designated to include the Rio Grande corridor and bordering riparian bosque, bounded by the riverside drains and Low-Flow Conveyance Channel (LFCC). The shallow groundwater system in this zone is typically recharged by river seepage. Boundary conditions providing significant control on the shallow riparian groundwater elevations include regional groundwater elevations and riverside drain and LFCC stage. Three MODFLOW packages were used to specify boundary conditions within the model. The River Package (RIV) was used to address the three types of surface water conditions within the model: in-channel Rio Grande stage; overbank Rio Grande water elevation; and, riverside drain or LFCC stage. The Riparian Package (RIP) (Maddock and Baird, 2003) was used to represent riparian vegetation classes and evapotranspiration rates. Model boundaries in layers 2, 3, and 4 were addressed using the General Head Boundary Package (GHB); this package was also used to set lateral boundaries in model layer 1 in areas lacking riverside drains, and the vertical boundary in layer 4. The handling of each of these boundary types is described below.

The wetted channel, water depth and occurrence of overbank flow vary according to Rio Grande flow magnitude. The specification of these characteristics constitutes the river boundary conditions for the groundwater models; because boundary conditions are flow-dependent, specific boundary conditions must be defined as a function of flow magnitude. For this study, the following flow magnitudes were selected: 100, 500, 1,000, 2,000, 3,000, 5,000, 7,000, and 10,000 cfs. For each selected flow magnitude, the wetted channel, water depth, and occurrence of overbank flow are identified through simulation with the FLO-2D flood routing model (Tetra Tech, 2004). The FLO-2D simulation results are used to build input files for the river package.

The riparian models employ a finer resolution grid than the FLO-2D model, allowing the location of the river to be more precisely delineated. Therefore, the integration of the two models required an association, or geographical shift, between the FLO-2D channel elements and the riparian model in-channel cells (Fig. 2). This procedure results in the assignment of a water surface elevation to every identified cell within the riparian model channel banks. However, because flow does not necessarily occur over the entire channel width (bank to bank), a correction factor is needed to control the seepage through the river bottom to that which would occur given the actual width of the wetted area. This correction factor is taken as the ratio between the FLO-2D computed channel width for the given flow magnitude and the FLO-2D maximum channel width. This correction factor is implemented with the river conductance term.

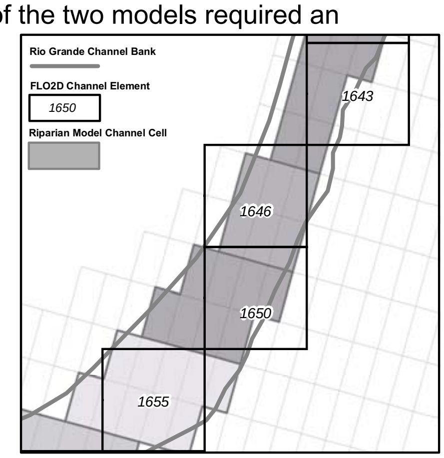

Figure 2. Associating FLO-2D and riparian model cells

In addition to modeling in-channel hydraulics, FLO-2D determines when flow exceeds the channel capacity and in such cases, models the distribution of overbank flow throughout the model grid. The process of integrating the FLO-2D over-bank elements with the riparian model grid was based on geographical overlay and did not include cell-by-cell shifting. Overbank water surface elevations were calculated from the FLO-2D model, superimposed on the riparian model grid, and the total percentage coverage of each riparian model cell by flooded FLO-2D cells was calculated. This percentage was then used to calculate a weighted-average water-surface elevation for the flooded portion of each riparian cell. Riparian model overbank cell conductance was scaled by the percentage of the cell flooded.

The GHB Package was used to specify boundary conditions on the riparian models at the sides and bottom of the active model domain. Simulated groundwater elevations were extracted from the regional USGS Groundwater Flow Model of the Albuquerque Basin (McAda and Barroll, 2002) and the NMISC Regional Groundwater Flow Model for the Socorro Basin (Shafike, 2005). These regional models were also used to set initial model heads and as a basis for assigning layer hydraulic properties. Each riparian model is discretized in the vertical direction into four layers. Model layer thicknesses directly below the bed of the Rio Grande are 20, 30, 30, and 100 feet respectively. Layers are extended orthogonally from the river, so that layer bottom elevations are constant along model rows. Layer 1 thickness varies with land surface elevation. Layers 2 and 3 are 30 feet thick throughout; Layer 4 is 100 feet thick throughout.

Water depletions in the riparian corridor occur through evaporation from open water and wet soil and through evapotranspiration (ET) from riparian vegetation. The RIP Package was used to represent riparian vegetation classes and ET rates for eight vegetation groups identified based on available vegetation classification coverages (USBR, 2004). For each vegetation group, an ET rate-with-depth curve was developed and implemented in the RIP package.

However, ET rates in the Middle Rio Grande region vary not only by plant type and depth to groundwater, but also by season. Seasonal variability can equal or exceed variability due to differences in plant type or depth to groundwater. The RIP package is designed to handle temporal variability via specification of additional plant groups with different ET rate-with-depth curves and maximum ET rate values. However, this becomes unwieldy if the intent is to vary ET rate in each of 10 to 12 stress periods for 8 plant groups. Accordingly, we implemented temporally varying ET rates in the riparian model RIP packages by varying the percentage coverage of each vegetation group within each cell as a function of time within the growing season. A hypothetical curve describing the variation of ET with time for a variety of plant groups at sites within the Middle Rio Grande was developed based on available monthly ET data (Fig. 3). The hypothetical curve was then used to calculate an ET weighting factor for each model stress period within a given transient run (Fig. 4), and the weighting factor used to scale percentage plant sub-group coverage for each sub-group within each active model cell for that stress period. The same weighting factors were used for each of the vegetation categories. Weighting factors ranged from 0 to 2.4, with 1.0 representing 8.33% (one twelfth) of the annual ET. Values smaller than 1.0 are used during winter periods when there is little or no transpiration and evaporation; values greater than 1.0 are used during summer periods.

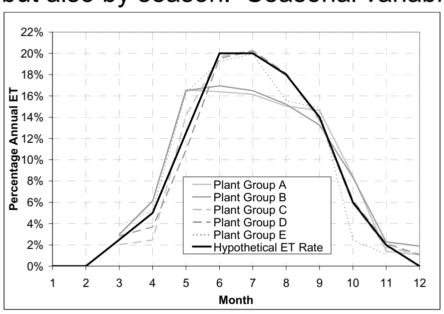

Figure 3. Hypothetical ET rate curve

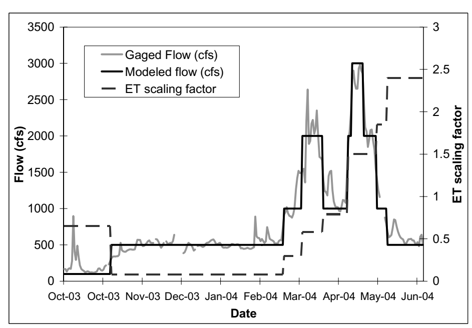

Figure 4. Transient model step-hydrograph, 2003-2004, and ET rate scaling factor by stress period

PRELIMINARY MODEL RESULTS

Preliminary simulations were made using each of the five models to assess the reasonableness of the models. The simulations included steady-state runs at each of the selected river flow levels, and transient runs in which a spring run-off period was simulated following several preceding fall and winter months. For the transient simulations, step-function hydrographs were first prepared from the daily river hydrographs, using the library of flows used to develop the suite of river boundary conditions (Fig. 4). The hydrographs only roughly approximate the actual progression of flows; finer resolution simulation of the spring pulse may be desired in some

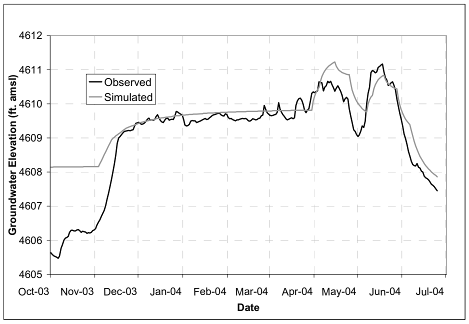

Figure 5. Modeled vs. Simulated, well ESC-E04A, Socorro model

applications and should be implemented in such cases. The first stress period was set as a steady-state, providing the initial condition for the subsequent transient stress periods corresponding to each change in the step-function hydrograph. Where available, observation well data were compared to simulated water levels as a check on model performance (Fig. 5). The comparisons indicated that the models perform within a reasonable range. However, a rigorous calibration was not conducted. Model calibration to local conditions using the most up-to-date data is recommended prior to application of the models to specific restoration questions.

The models were then used to evaluate hypotheses regarding potential conditions within and surrounding the riparian groundwater zone and to illustrate how water levels and river seepage rates are affected under different circumstances, including alternate vegetation, regional water level, and antecedent water supply conditions. These results, while best considered "qualitative" due to the number of assumptions built into the test cases, provide insight into riparian zone responses that may be important to water management and river restoration actions. For this application, the historic base case was used to represent conditions prior to, during, and following a spring run-off pulse. Then, modifications were made to various elements of the base case to test hypotheses regarding the riparian groundwater system and groundwater-surface water interactions through the spring run-off cycle. Results are briefly described below.

- *Alternate riparian vegetation*: It was assumed that riparian vegetation classes with maximum evapotranspiration rates of 4 acre-feet per year were replaced with vegetation classes with maximum evapotranspiration rates of 3 acre-feet per year. Given the assumed distribution of riparian vegetation classes and associated rates for the modeled regions, the simulated groundwater elevation difference ranged from 0 to 2.5 feet, with elevated groundwater under the alternate vegetation assumption. Under the alternative vegetation assumption, the river seepage loss was reduced by 0.1 - 0.2 cfs/mile, and water lost to ET was reduced by up to 25%. Impacts were more noticeable in the southernmost model, the Socorro model, and for all models were greatest where higher-ET vegetation classes were concentrated.
- *Alternate regional groundwater conditions*: Model boundaries were adjusted from the base case to represent modified, hypothetical regional groundwater and drain boundary elevations. Under the lower regional condition assumptions, the riparian corridor was significantly "drier" and increased river seepage rates occurred, although the degree of change was variable by model reach and by season. A drier corridor would impact the maintenance of target river flows for habitat, particularly in low flow periods; also, greater losses throughout the season would have impacts on water delivery via the river channel.
- *Alternate antecedent conditions*: Assumptions were made regarding river flows that might typify a low or high supply antecedent period, i.e., a period of several years drought or above-average supply. As simulated in this scenario, the impact of the antecedent condition was evident only immediately following the condition, and was minimal by the beginning of the spring runoff. However, in practice, low antecedent flow conditions will likely result in altered boundary conditions. The degree to which boundary conditions are altered, how persistent the boundary conditions are during and following the spring event, and the magnitude and duration of the spring runoff will work in concert to determine the full impact of antecedent conditions.

IMPLICATIONS FOR WATER MANAGEMENT

The primary insight derived from the simulations is that the riparian environment is a dynamic environment impacted by multiple processes that manifest differently under different conditions, with inter-relationships among environmental components including groundwater, surface water and vegetation. These dynamics have implications for both water management and restoration activities, and provide the basis for understanding seasonal changes in seepage rates and shallow groundwater conditions that may be critical to the success of a river or bosque restoration project. The riparian models can be used in a number of ways to support restoration activities, including:

- *Site selection/assessment*: Simulations can be conducted to assess general characteristics, for example, anticipated ranges of river seepage under various operations, or maintenance of desired shallow groundwater conditions in the riparian zone.
- *Feasibility studies*: Alternate restoration approaches can be simulated and assessed to identify whether the project is likely to achieve hydrologic objectives under an expected range of potential climate and water supply conditions.
- *Project design*: Projects that have been selected for design and construction can be modeled to fine-tune design elements.
- *Project monitoring and operations/maintenance*: Hydrologic data pertaining to a project can be monitored and used to refine model characteristics for the project area. Then, change under forecasted or potential future conditions can be simulated, possibly providing an opportunity to identify and implement additional project controls to improve project success.

Depending on the nature of a specific application, the riparian models can be used with varying degrees of refinement. To support site selection and assessment, relatively limited refinements would be needed. Appropriate levels of model refinement increase through the progression from assessment, feasibility study to design. Through this progression, model refinement should be supported with increasing levels of locally relevant data, including reach-specific paired river and drain seepage runs and concurrent water-level monitoring in shallow piezometers within the reach. Regional aquifer boundary conditions, presently adapted from the regional models, should be re-assessed for appropriateness in the context of the proposed restoration and projected regional conditions.

Key among water management priorities is the efficient conveyance of water to meet demands, whether the demand is driven by urban, agricultural, environmental or interstate compact needs. The efficient conveyance of water requires knowledge of river and drain seepage losses/gains under alternate supply, regional and routing conditions. While river and drain seepage losses/gains can be quantified through field investigation, it would be impractical and expensive to conduct enough field investigations to characterize the losses/gains under all potential conditions that may be important to water management. For example, river seepage losses are dependent on concurrent drain stage and other conditions. Should these conditions vary due to modified system operations, groundwater elevations or other processes, variation of river seepage rates will also occur. The ability to transfer knowledge gained under one set of conditions to another set of conditions can be rapidly assessed using modeling tools such as the riparian models, assuming that a sufficient range of measured information is available for model calibration.

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