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EVALUATION OF RIO GRANDE MANAGEMENT ALTERNATIVES USING A SURFACE-WATER/GROUND-WATER MODEL[1]

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ABSTRACT: Previous investigations observed significant seepage losses from the Rio Grande to the shallow aquifer between Socorro and San Antonio, New Mexico. High-resolution telescopic modeling was used along a 10-km reach of the Rio Grande and associated drains and canals to evaluate several management alternatives aimed at improving river conveyance efficiency. Observed data consisted of ground-water and surface-water elevations, seepage rates along the Rio Grande and associated canals and drains, and borehole geology. Model calibration was achieved by adjusting hydraulic conductivity and specific storage until the output matched observed data. Sensitivity analyses indicated that the system was responsive to changes in hydrogeologic properties, especially when such alterations increased vertical connectivity between layers. The calibrated model predicted that removal of the low flow conveyance channel, a major channel draining the valley, would not only decrease river seepage by 67%, but also decrease total flow through the reach by 75%. The decreased flow through the reach would result in increased water logging and an average increase in ground-water elevations of 1.21 meter. Simulations of the system with reduced riparian evapotranspiration rates or a relocated river channel also predicted decreased river seepage, but to a much lesser degree.

(KEY TERMS: aquifer characteristics; evapotranspiration; surface-water/ground-water interactions; geospatial analysis; MODFLOW simulation; riparian management.)

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INTRODUCTION

Rivers of the southwest play a key role in sustaining life in arid regions. The Rio Grande flows through Colorado, New Mexico, and Texas and is the 24th longest river in the world, with a watershed covering 11% of the continental United States. Maintaining adequate streamflow is essential to preserving aquatic and riparian habitat along the Rio Grande and protecting endangered species. Human activities make many urban, agricultural, and industrial demands on this finite resource. In addition to anthropogenic diversions from the Rio Grande, natural reductions in streamflow can be attributed to seepage from the river channel, evaporation from the river and other surface-water bodies, and transpiration by riparian vegetation.

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The Socorro reach of the Rio Grande extends from San Acacia to San Marcial, New Mexico (Figure 1). Diversion for crop irrigation is the main anthropogenic activity that reduces river flow downstream of San Acacia. Irrigation water that is not evapotranspired recharges the shallow aquifer and eventually returns to the Rio Grande and associated shallow ground-water system. Shafike (2001) estimated the average annual water depletion in the Socorro reach at 1.52×10^8 m^3, with 52% going to riparian evapotranspiration (ET), 27% to crop ET, 8% to open-water evaporation, and 12% to ground-water outflow (Figure 2).

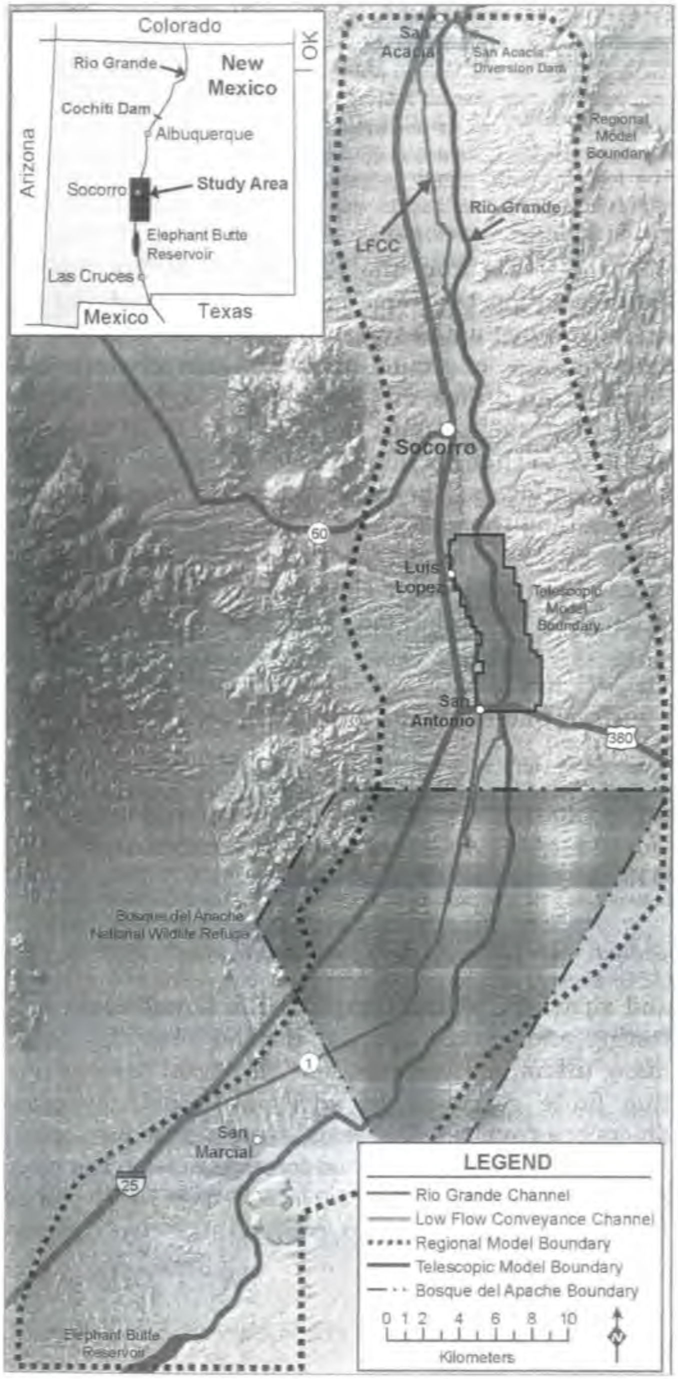
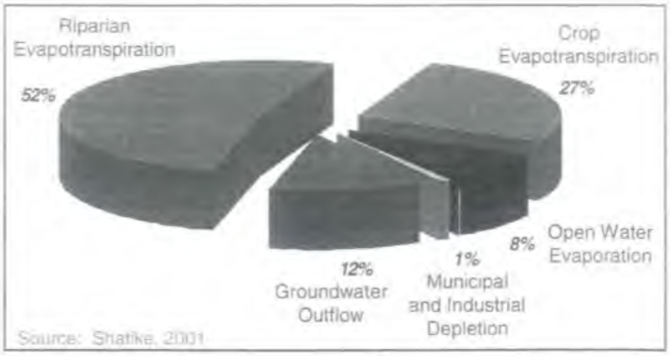


FIGURE 1. Location Map With Regional-Scale and Telescopic Model Boundaries.



Source: Shafike, 2001

FIGURE 2. Estimated Reductions in River Flow Along the Socorro Reach in 2002.

The New Mexico Interstate Stream Commission developed a regional-scale model to evaluate surface-water/ground-water interactions and total water depletion in the Socorro reach (Shafike, 2001). The regional model extends from San Acacia to the headwaters of Elephant Butte Reservoir (Figure 1) and simulates physical processes such as surface-water routing, surface-water/ground-water interactions, discharge from springs, riparian and crop depletions, ground-water withdrawals and ground-water levels. The model outputs include ground-water elevation, surface-water flow, and riparian and crop depletion. The model was calibrated to surface-water seepage rates, flows, and ground-water elevation. Field data obtained in 2000 and 2001 for the river reach between Luis Lopez and San Antonio indicated high spatial and temporal variability in seepage loss (SSPA, 2002).

The goal of this investigation was to develop a refined model of the 10-km long, Luis Lopez to San Antonio reach of the Rio Grande that could be applied to evaluate river management alternatives within that reach. To achieve this goal, conceptual and numerical modeling of water levels and flow patterns of the Rio Grande, in the connected shallow aquifer, and in associated canals and drains was performed. Steady-state and transient ground-water models were used to simulate the behavior of ground-water and surface-water systems and to analyze potential management scenarios.

The specific objectives of this study were to (1) develop a conceptual understanding of the ground-water and surface-water interactions in the Luis Lopez to San Antonio reach; (2) incorporate existing geologic and hydrogeologic information into the numerical model of the reach; and (3) simulate management alternatives for optimizing river conveyance efficiency and maintenance of river flows.

STUDY AREA

The study area is characterized by a high-desert semiarid climate typical of New Mexico. During the period from 1914 to 2002, average annual temperatures ranged from 5 to 23°C, while average annual precipitation for the same 88-year period was 24 cm including 17 cm of snowfall (WRCC, 2003). Approximately 60% of precipitation fell during the months of July, August, September, and October.

The Rio Grande follows a path along the active Rio Grande rift. The Socorro basin is one of many subbasins along the Rio Grande and is marked at its northern and southern termini by San Acacia and Elephant Butte. Rocks range from Precambrian to Holocene. The Santa Fe Formation is the primary geologic unit between the basin bedrock and Quaternary alluvium deposits and consists mainly of aggradational basin fill sourced from Rio Grande rift deposits (Anderholm, 1987). Estimates of its thickness determined by gravity surveys range from 0 to 1,524 meter (Sanford, 1968; Shafike *et al.*, 2002). The thickest section of the Santa Fe Formation within the Socorro reach underlies the Quaternary alluvium near San Antonio (Figure 1). The Santa Fe Formation represents the principal aquifer in the state of New Mexico; its upper boundary is defined by an unconformity between it and overlying fluvial quaternary deposits (Cather, 1997). These fluvial deposits have a maximum thickness of approximately 30 meter.

Historically characterized as a naturally meandering channel, the Rio Grande has become a controlled river, being intercepted by many dams and diversion structures along its path through Colorado, New Mexico, and Texas. One of these diversion dams is located at San Acacia, where flows are regulated and diverted into irrigation canals for the Socorro reach. Several features make this reach of the river unique, including the low flow conveyance channel (LFCC) which plays a major role in the hydrodynamics of the reach (Figures 1 and 3). Running from San Acacia Diversion Dam to Elephant Butte Reservoir, the LFCC was constructed following the prolonged drought of the 1950s as a means to convey water, more efficiently to Elephant Butte reservoir. The LFCC is a 15-meter wide rock-lined channel with a bottom elevation lower than the river bed, making it the topographic low for most of the Socorro reach (Figure 3). The LFCC has a maximum capacity of 57 m^3/s and was used at its maximum capacity from 1959 until early 1985, when Elephant Butte reservoir became full. In March 1985, diversions from the Rio Grande into the LFCC at San Acacia were terminated, and since that time, the channel has functioned strictly as a drain.

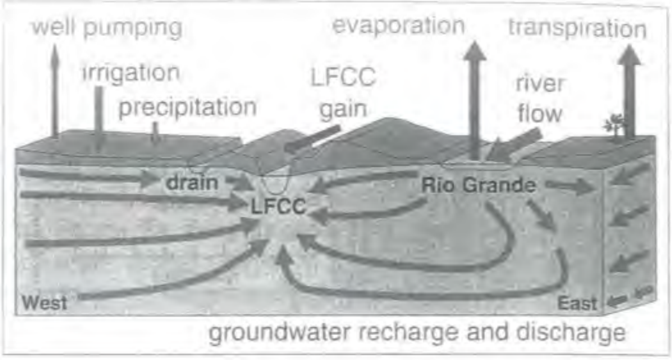


FIGURE 3. Conceptual Model of the Shallow Ground-Water Flow System Near San Antonio.

In addition to the LFCC, there are irrigation canals, ditches, and drains that characterize the study area and service the agricultural activities in the valley west of the Rio Grande. Several minor ungaged tributaries between San Acacia and San Marcial contribute flows to the Rio Grande during summer storms and other precipitation events. These ungaged tributary inflows were considered in the regional model as mountain front recharge. Ground water is replenished by Rio Grande seepage, precipitation, and mountain front recharge. A conceptual model of ground-water flow in the reach (Figure 3) shows river seepage following a topographic gradient towards the LFCC (Anderholm, 1987; Roybal, 1991).

The majority of irrigated land is in alfalfa production with other crops including chile, corn, and pasture. Riparian vegetation is dominant in the area adjacent to the Rio Grande and LFCC, where woody vegetation consists primarily of nonnative salt cedar (*Tamarix ramosissima*), Russian olive (*Eleagnus angustifolia*), cottonwood (*Populus deltoids and angustifolia*), and honey mesquite (*Prosopis glandulosa*) (Tetra Tech Inc., 2003; Moore *et al.*, 2004). Various shrubs and grasses also characterize the riparian community.

METHODS

Hydrologic Characterization

Monthly ground-water elevations were measured and recorded in ten wells within the model domain

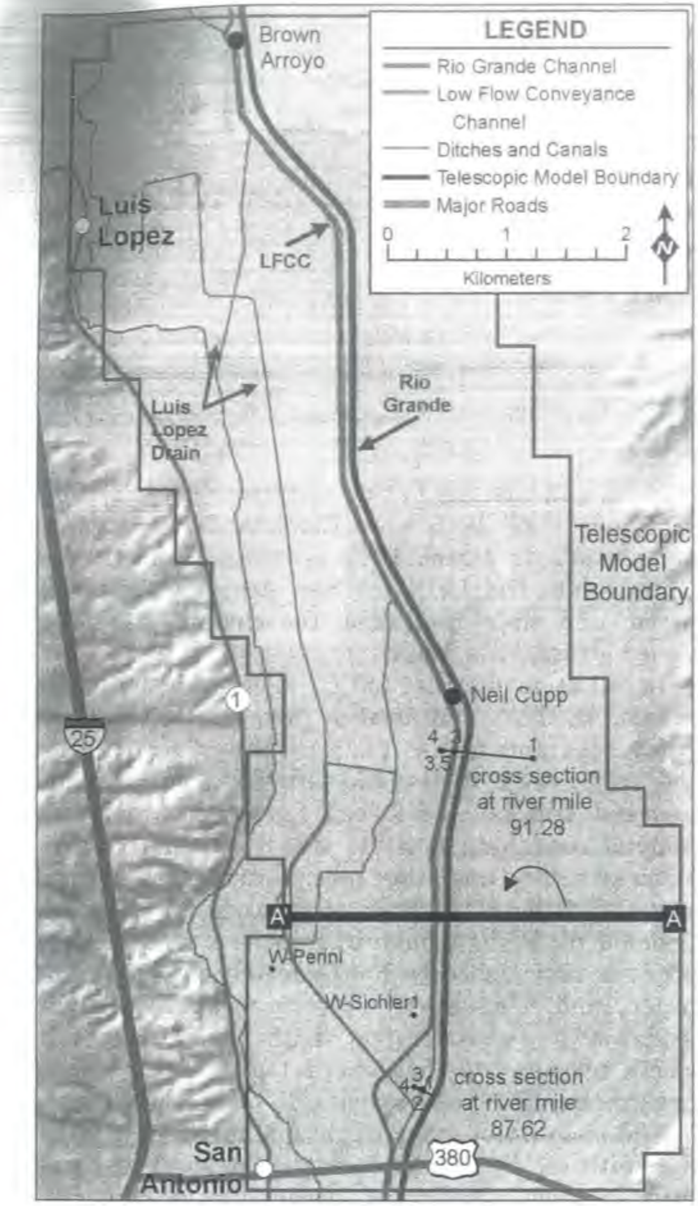


FIGURE 4. Locations of Telescopic Model Domain, Surface-Water Features, Area Landmarks, and Wells Monitored October 2001 Through July 2003.

between October 2001 and August 2003 (Figure 4). Surface-water elevations were collected monthly at 45 locations along the LFCC, Rio Grande, Brown Arroyo, and associated canals, drains, and ditches from October 2002 through August 2003 to determine flow trends. Surface-water elevation measurement locations were chosen to be approximately every 1.6 km along each conveyance and at all major canal, drain, and ditch intersections. River and LFCC bed elevations for the telescopic model were interpolated from regional model values.

Stratigraphic and grain-size distribution analyses from two cross sections at river miles 91.28 and 87.62 were based on split-spoon samples collected at 0.3-meter intervals with a 3.82 cm diameter sampler driven by hammer (Figure 4). Data showed that the upper 31 meters of sediment underlying the floodplain was composed primarily of unconsolidated sand, gravel, and silt. A 0.6-meter thick discontinuous fine-grained layer was located at roughly 9 meters below the surface. No significant faults were detected within the Quaternary alluvium. The vertical grid of the telescopic model was refined according to the geologic data. The Quaternary alluvium was divided into three conceptual layers for the telescopic model (i.e., two aquifers separated by a single fine-grained layer).

Two aquifer pumping tests were performed within 1.6 km of the southern telescopic model boundary to characterize aquifer properties. The first aquifer test was analyzed using the Hantush method and yielded horizontal and vertical hydraulic conductivity values of 46 and 25 m/day, respectively, specific storage of $1.5 \times 10^{-4}\ \mathrm{m}^{-1}$, and specific yield of 0.035. The second aquifer test was analyzed by solving Theis and Cooper-Jacob equations and yielded horizontal hydraulic conductivity values of 10 and 13 m/d and specific storage values of $1.5 \times 10^{-4}\ \mathrm{m}^{-1}$ and $1.6 \times 10^{-4}\ \mathrm{m}^{-1}$, respectively. The lower hydraulic conductivity determined in the second aquifer test likely reflected differences in local geology between the two sites.

Hydrologic Modeling

The regional-scale surface-water and ground-water model of the Rio Grande reach from San Acacia to Elephant Butte reservoir (Figure 1) provided boundary conditions for the telescopic model that is the focus of this study. Boundary conditions were prescribed for the telescopic model by assigning heads along the model perimeter equal to values of simulated heads for Layer 1 of the regional-scale model. The boundary between the bottom layer of the telescopic model and Layer 2 of the regional-scale model was assumed to be a along the model perimeter only. The regional-scale model included the entire Rio Grande basin sediments of the Santa Fe Formation and Quaternary alluvium (Shafike, 2005). The Quaternary alluvium was treated as model layer one in the regional-scale model.

MODFLOW (McDonald and Harbaugh, 1988), with extensions and supplemental programs Riv2 (Miller, 1988), stream package (Prudic, 1989), and MODBRANCH (Swain and Wexler, 1996), were used to simulate the water movement among the LFCC, Rio Grande, Santa Fe Formation, and Quaternary alluvium aquifers. The physical interactions were reflected in the regional-scale model in terms of surface-water routing, surface-water and ground-water interactions, discharge from springs, riparian and crop depletions, ground-water withdrawals, and ground-water levels. Ground-water levels at the boundaries of the telescopic model were based upon simulated heads in the regional-scale model and remained unchanged throughout all simulations.

The telescopic model grid for the 10-km long by 5-km wide domain consisted of 320 rows and 170 columns, for a total of 54,400 cells with a uniform grid cell size of 30.5 meters by 30.5 meters. Only cells within the Quaternary alluvium were active. Steady-state and transient simulations used the same model grid.

Steady-state simulations were performed to determine initial head values for active grid cells of the telescopic model. These simulations displayed changes in the water table in response to variations in geology and river management scenarios. Steady-state head values were used as initial heads for the transient model runs. The transient model was used to show changes in water level elevations and water budget with time and for predictive analyses.

Three distinct units were identified (i.e., the fine-grained layer at approximately 9-meter below ground surface sandwiched between thicker sand and gravel units). These units were conceptualized as shown in Figure 5 and the total thickness of the Quaternary alluvium ranged from 10 to 30 meter. Model ground surface elevation was determined as an average for each 30.5-meter by 30.5-meter model grid cell from a 10-meter resolution digital elevation model (USGS, 1999). The thickness of Layer 1 was defined as the vertical distance between the land surface and the top of the fine-grained layer. Linear interpolation between observed depths of the fine-grained layer was applied across each of two cross sections at river miles 91.28 and 87.62 in the east-west orientation (Figure 4). Linear interpolation was applied a second time in the north-south direction to assign a Layer 1 thickness value to each cell. Layer 2, the fine-grained layer, was assumed to have a constant thickness of 0.6 meter throughout the model. Layer 3 was determined as the thickness of the Quaternary alluvium from the bottom of the fine-grained layer to the top of the Santa Fe Formation as represented in the regional-scale model. Layer 1 thickness ranged from 3 to 11 meters with the thickest area occurring at the north beneath the present-day river channel. Layer 3 thickness ranged from 6 meter to a maximum of 23 meter beneath the current river channel in the south. Initially, Layers 1 and 3 were assigned horizontal and vertical hydraulic conductivity values of 31 and 15 m/day, respectively. These values were the same as those applied to the uppermost layer of the regional-scale model, were within the range of aquifer test results, and typically represent well sorted sands and gravel (Freeze and Cherry, 1979). Layer 2 was assigned values typical for silty sand, with a horizontal conductivity of 0.6 m/day and vertical conductivity of 3.0×10^{-2} m/day (Freeze and Cherry, 1979). Based on the pump test results, all three layers were assigned values of 3×10^{-6} m^{-1} for specific storage and 0.2 for specific yield.

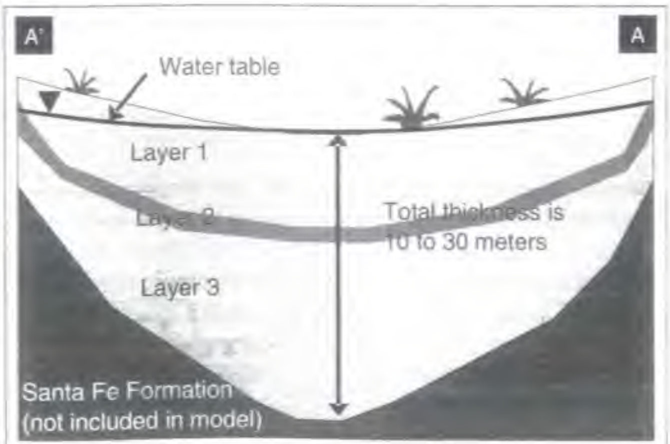


FIGURE 5. Hypothetical Cross-Section of the Rio Grande Floodplain With Confining Layer 2.

The ET package of MODFLOW was used to simulate direct evaporation and plant transpiration. IKONOS satellite imagery from July 2000 was used to assign land use classifications of crop, riparian, sandbar, and inactive. Each model grid cell was assigned a percentage of surface area occupied by each vegetation type. Estimations of ET rates for various riparian vegetation types in the year 1999 were obtained from eddy covariance tower data collected near the study area (Cleverly *et al.*, 2002). Riparian ET rates measured at the Bosque del Apache tower varied from 0.9 to 1.2 m/year. The steady-state model did not include crop ET because available data represented a period of inactive agriculture (no water in agricultural drains and no irrigation). For the transient model, ET from crops was simulated during the months of April through October. Crop ET was assumed to be less than applied irrigation and thus the sum was treated as a deep percolation recharge term in MODFLOW and applied to each cell based on the percentage of crop vegetation covering that cell. The agricultural deep percolation term was assumed to be 0.3 m/year/acre, similar to what has been used for the middle Rio Grande basin model (McAda and Barroll, 2002).

The MODFLOW river package (McDonald and Harbaugh, 1988) was used to simulate the connection between the Rio Grande, LFCC, agricultural drains, and the shallow aquifer. This was accomplished by using leakage terms to identify flows to and from surface features. For the transient-state simulations, synthetic data were applied to represent Rio Grande stage variations in character and magnitude that were based on observed USGS gage readings at San Marcial USGS station 08358300 (USGS, 2003). Stage values for the LFCC and agricultural drains and canals were assigned a constant value of 0.6 meter above the bed elevation.

The telescopic model was calibrated under steady-state and transient conditions to match observed ground-water elevations and river seepage. Further detail on model construction and calibration may be found in Wilcox (2004). Following calibration, the model was run under transient conditions to simulate hydrological responses to river management alternatives.

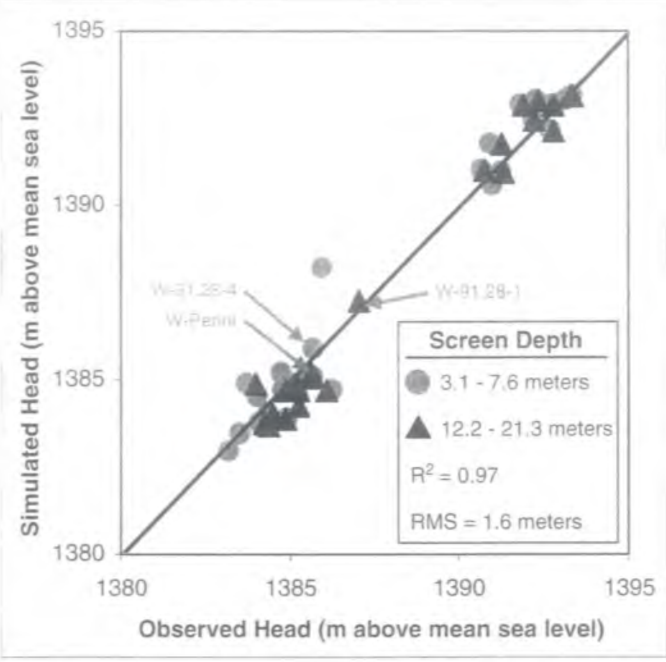


FIGURE 6. Observed and Simulated Heads for the Steady-State Telescopic Model.

RESULTS

Telescopic Model Calibration and Sensitivity Analyses

Telescopic model steady-state results indicated patterns of seepage loss and gain that were consistent with the observed behavior of the river and the LFCC. Results were also in reasonable agreement with the simulated water table from the regional-scale model. Simulated and observed head data collected in May 2003 are displayed in Figure 6. Root mean squared (RMS) and R^2 values of residuals were 1.59 and 0.97 meter, respectively, indicating good correlation between the observed and simulated data. Measured seasonal fluctuations in water level elevations in ten wells during 2002 had an RMS value of 0.8 meter.

The transient model was run for two years with a time step of three days. Each stress period was set at one month and consisted of a group of ten time steps, facilitating inclusion of monthly fluctuations in riparian ET and river stage. Observed water levels were compared with simulated data at ten well locations within the domain. Simulated *vs.* observed head values at three separate locations show representative trends (Figure 7). Simulated water levels were consistently higher than observed levels. Final calibration was achieved by making minor changes to river stage for each stress period until the hydrograph fluctuations matched in character and magnitude. The sharp changes observed in simulated water level elevation data resulted from the discrete monthly changes in stage and riparian ET rate values.

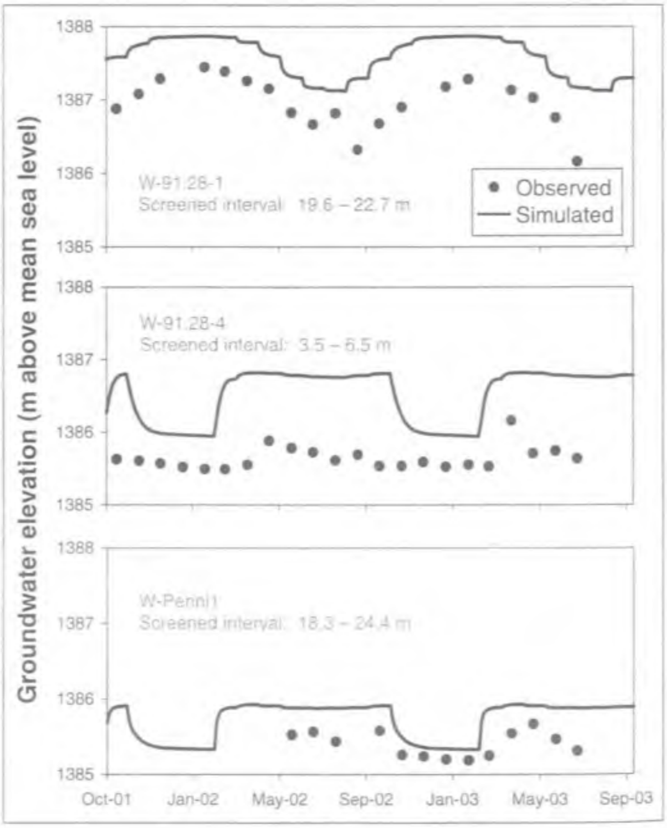


FIGURE 7. Simulated and Observed Heads From the Transient Telescopic Model at Three Representative Locations. Well locations are shown in Figure 4.

Sensitivity analyses were performed to evaluate the importance of three major assumptions of the conceptual model [i.e., (1) the existence of three

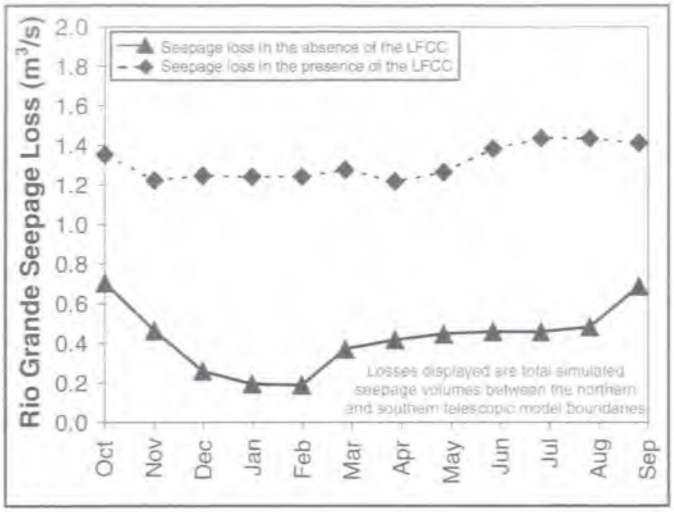


FIGURE 8. Simulated Time-Series Plot of Rio Grande Seepage Loss in the Presence and Absence of the LFCC.

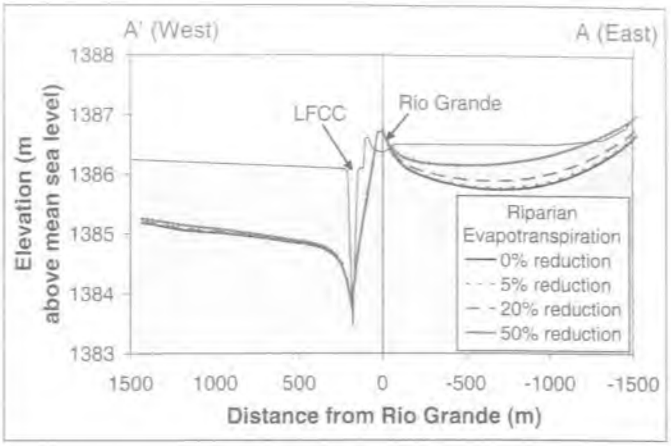


FIGURE 9. Cross-Section of Simulated Water-Level Elevations at Row 260 of the Telescopic Model With Varying Rates of Riparian Evapotranspiration.

distinct hydrogeologic units of differing hydraulic properties, (2) the presence of a continuous layer of low-permeability sediment at 9-meter depth, and (3) the sediments underlying the Rio Grande possessed the same hydrologic characteristics as the surrounding Quaternary alluvium]. These assumptions suggested that deeper screened wells in Layer 3 would display characteristics of a confined aquifer as indicated by aquifer test results. Steady-state simulations were used to test assumptions regarding composition of the subsurface geology including changes in anisotropy and hydraulic conductivity.

The telescopic model was highly sensitive to changes in vertical connectivity between the Layers 1, 2, and 3, the ratio of horizontal to vertical hydraulic conductivity, and the absolute values of hydraulic conductivities assigned to each layer. Details on the results of the sensitivity analyses may be found in Wilcox (2004).

Simulation of Management Alternatives

The steady-state and transient telescopic models were used to evaluate the effects of hypothetical management scenarios on the functioning of the study area's hydrologic system. The three scenarios investigated were as follows: (1) Rio Grande seepage behavior in the absence of the LFCC, (2) removal of riparian phreatophytes, and (3) relocation of the river channel. The discussion below emphasizes the effects of management alternatives on seepage from the Rio Grande and changes in ground-water levels; related effects such as flow of ground water in and out of the model domain are discussed in Wilcox (2004).

As the topographic low in the system, the LFCC acts as a drain for the entire valley. Seepage from the Rio Grande to the LFCC has resulted in decreased river flows, with attendant consequences for downstream deliveries and the riparian environment. Filling in the LFCC has been proposed to decrease river seepage, although this alternative would be costly and disruptive. A simulation was performed to evaluate the response of the hydrologic system over time in the absence of the LFCC. A time-series plot of river seepage between the northern and southern extents of the telescopic model with and without the LFCC shows the predicted monthly losses from the Rio Grande (Figure 8). The predicted decrease in seepage in the absence of the LFCC is most pronounced during the winter months. Results indicated that without the LFCC, river seepage and net boundary influx would decrease by 67 and 72%, respectively. Total flow (ground water and surface water) through the system was predicted to decrease by 75%, indicating increased water logging and reduction in downstream delivery. The decreased flow through the reach resulted in an average increase in ground-water elevations of 1.21 meter. In response, ET would increase by 8% due to elevated water levels in the shallow aquifer and resultant increased water uptake by riparian vegetation. The elevated ground-water levels result in a predicted decrease of leakage to the aquifer from agricultural canals and drains to the extent that they become gaining components of the surface-water system.

In recent years, millions of dollars have been spent on removal of salt cedar and other nonnative invasive vegetation with the goal of reducing transpirative losses and thereby increasing Rio Grande flows (Tetra Tech Inc., 2003). We therefore investigated the effects

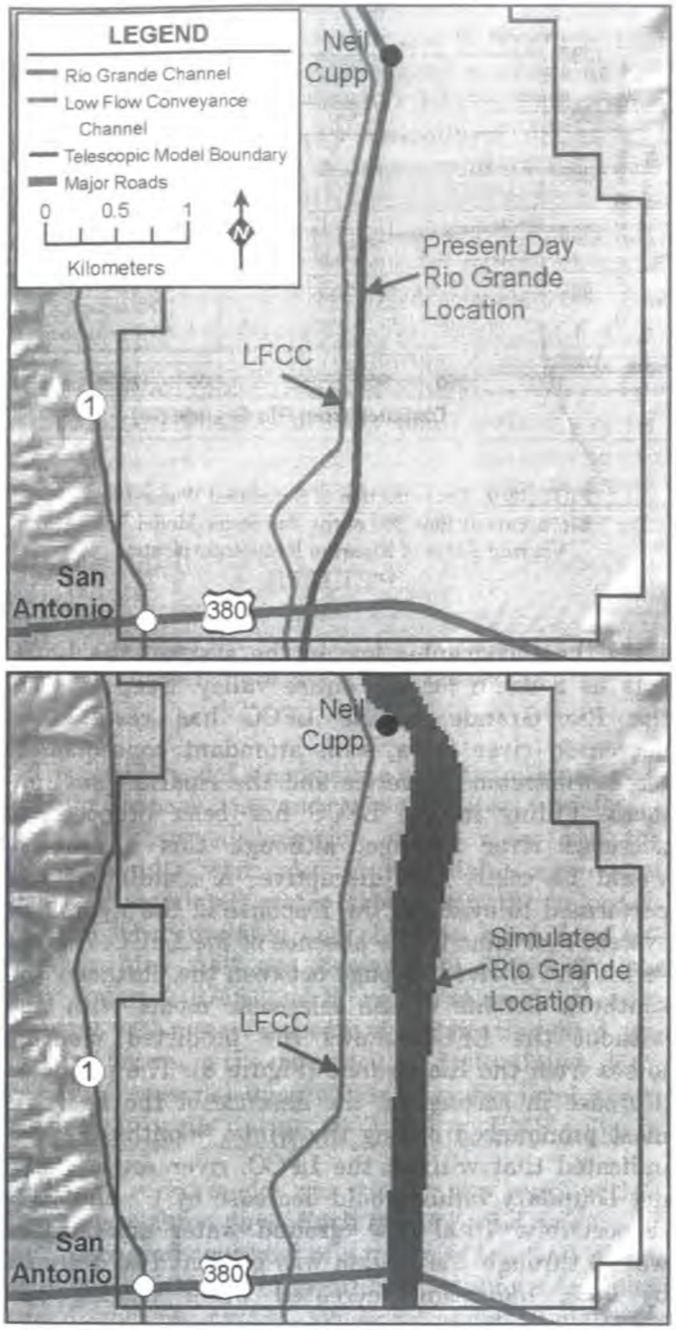


FIGURE 10. Present-Day and Simulated Locations of the Rio Grande Channel.

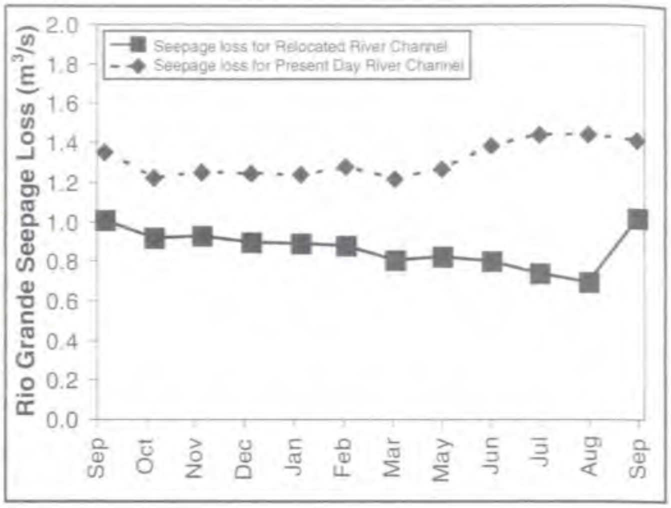


FIGURE 11. Simulated Rio Grande Seepage Loss for Relocated and Present-Day River Channel Locations.

of decreased riparian ET on streamflow in our modeled domain. Simulated ET values for riparian vegetation and bare ground were decreased by 5, 20, and 50% in the steady-state model without changing other model parameters. For 5 or 20% reductions in ET the predicted decreases in Rio Grande seepage were a relatively minor 1 or 2%, respectively. A much larger effect is predicted if ET decreases by 50%, resulting in a reduction in river seepage of 6%. Similarly, the effect on predicted ground-water levels is significant only with a 50% decrease in riparian ET (Figure 9).

The third management alternative evaluated shifting the Rio Grande channel to the east to lessen the gradient between the river and the LFCC and restore the river to a more natural, pre-1950s condition (Figure 10). To simulate the system with a shifted, wider channel, a new river input file was created for the transient model. Input to the transient model was taken from the initial steady-state run in which simulated heads were recorded with the LFCC and river in their present day configuration. River cells in the new input file remained active for the entire year. Results of the transient simulation predict that Rio Grande seepage would decrease by approximately 34% after channel widening and relocation. Water table levels would also decrease west of the LFCC, resulting in increased seepage from drains (13%) and decreased ET (2%). The predicted changes in river seepage throughout the year are shown in Figure 11. Rio Grande seepage losses from the proposed channel location decreased due to the increased distance from the LFCC and a lower river bed elevation.

CONCLUSIONS

High-resolution telescopic modeling analysis was used along the Rio Grande and associated drains and canals to evaluate several management alternatives aimed at improving river conveyance efficiency. Sensitivity analyses indicated that the system was responsive to changes in hydrogeologic properties, especially when such alterations increased vertical connectivity between layers. It was predicted that removal of the valley's topographic low, the LFCC, would greatly decrease seepage losses from the river in the modeled reach, but would increase water logging and worsen conveyance efficiency. Simulations of the system with decreased ET rates and a relocated river channel showed smaller effects on system hydrodynamics.

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LITERATURE CITED

Anderholm, S.K., 1987. Hydrogeology of the Socorro and La Jencia Basins, Socorro County, New Mexico. U.S. Geological Survey Water-Resources Investigations Report 84-4342, Department of the Interior, Denver, Colorado.

Cather, S.M., 1997. Toward a Hydrogeologic Classification of Map Units in the Santa Fe Group, Rio Grande Rift, New Mexico. New Mexico Geology 19(1):15-21.

Cleverly, J.R., C.N. Dahm, J.R. Thibault, D.J. Gilroy, and J.E. Allred Coonrod, 2002. Seasonal Estimates of Actual Evapotranspiration From *Tamarix Ramosissima* Stands Using Three-Dimensional Eddy Covariance. Journal of Arid Environments 52:181-197.

Freeze, R.A. and J.A. Cherry, 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

McAda, D.P., and P. Barroll, 2002. Simulation of Ground-Water Flow in the Middle Rio Grande Basin Between Cochiti and San Acacia, New Mexico. U.S. Geological Survey Water-Resources Investigations Report 2002-4200, U.S. Geological Survey, Denver, Colorado.

McDonald, M.G. and A.W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Groundwater Flow Model. U.S. Geological Survey Open File Report 83, U.S. Geological Survey, Washington, D.C.

Miller, R.S., 1988. User's Guide for RIV2 – A Package for Routing and Accounting of River Discharge for a Modular, Three-Dimensional, Finite-Difference, Ground-Water Flow Model. U.S. Geological Survey Open-File Report 88-435, U.S. Geological Survey, Denver, Colorado.

Moore, J., J. King, A. Bawazir, and T. Sammis, 2004. A Bibliography of Evapotranspiration With Special Emphasis on Riparian Vegetation. New Mexico Water Resources Research Institute Miscellaneous Report No. M28. http://wrri.nmsu.edu/publish/miscrpt/m28/m28.pdf, *accessed* July 23, 2005.

Prudic, D.E., 1989. Documentation of a Computer Program to Simulate Stream-Aquifer Relations Using a Modular, Finite-Difference, Ground-Water Flow Model. U.S. Geological Survey Open-File Report 88-729, U.S. Geological Survey, Denver, Colorado.

Roybal, F.E., 1991. Ground-Water Resources of Socorro County, New Mexico. U.S. Geological Survey Water-Resources Investigations Report 89-4083, U.S Department of the Interior, Albuquerque, New Mexico.

Sanford, A.R., 1968. Gravity Survey in Central Socorro County, New Mexico. New Mexico Bureau of Mines and Mineral Resources Circ. 91, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

Shafike, N.G., 2001. Surface Water–Groundwater Interactions Along the San Acacia to San Marcial Reach of the Rio Grande. Proceedings of the Conference of the American Water Resources Association (AWRA), Albuquerque, New Mexico, November 12-15, 2001.

Shafike, N.G., 2005. Linked Surface Water and Groundwater Model for Socorro and San Marcial Basins Between San Acacia and Elephant Butte Reservoir. *In:* Upper Rio Grande Water Operation Review, Appendix H, http://www.spa.usace.army.mil/urgwops/feis/Volume%202/URGWOPS%20FEIS%20Appendix%20J.pdf>, *accessed* October 2007.

Shafike, N., R.S. Bowman, and L.J. Wilcox, 2002. Hydrologic Modeling of the Rio Grande Surface Water/Groundwater System From San Acacia to Elephant Butte Reservoir. Proceedings of the Conference of New Mexico Water Research Symposium, Socorro, New Mexico, p. F30.

S.S. Papadopulos & Associates, Inc., 2002. Assessment of Flow Conditions and Seepage on the Rio Grande and Adjacent Channels, Isleta to San Marcial, Summer 2001. S.S. Papadopulos & Associates, Inc., Boulder, Colorado.

Swain, E.D., and E.J. Wexler, 1996. A Coupled Surface-Water and Ground-Water Flow Model (MODBRANCH) for Simulation of Stream-Aquifer Interaction. U.S. Geological Survey Techniques of Water-Resource Investigation Report 06-A6. U.S. Geological Survey, Denver, Colorado.

Tetra Tech, Inc., 2003. Hope for a Living River, a Framework for a Restoration Vision for the Rio Grande. The Alliance for Rio Grande Heritage, Albuquerque, New Mexico.

USGS (U.S. Geological Survey), 1999. EROS Data Center National Elevation Dataset – 7.5-Minute Raster Digital Elevation Data. U.S. Geological Survey, Sioux Falls, South Dakota.

USGS (U.S. Geological Survey), 2003. Real-Time Water Data for USGS 08358300 Rio Grande Conveyance Channel at San Marcial, NM. http://waterdata.usgs.gov/nm/nwis/, *accessed* on June 7, 2006.

Wilcox, L.J., 2004. Telescopic Model of Groundwater/Surface Water Interactions Near San Antonio, NM. Unpublished M.S. Thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

WRCC (Western Regional Climate Center), 2003. Precipitation and Snowfall Monthly Totals. Western Regional Climate Center, Reno, Nevada. http://www.wrcc.dri.edu, *accessed* July 10, 2003.