# Riparian Groundwater Models for the Middle Rio Grande: ESA Collaborative Program FY07

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**April 2008**

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# 1.0 INTRODUCTION

This report describes two shallow, riparian-zone groundwater models (riparian model), the Bosque del Apache and Fort Craig models, developed to represent the reach of the Rio Grande between the North Boundary of Bosque del Apache and the northern end of the Elephant Butte Reservoir, New Mexico (Figure 1.1). These models join an existing suite of six riparian models developed to represent physical processes relevant to assessing shallow groundwater conditions and exchanges between surface water and shallow groundwater within the floodplain of the Rio Grande from Cochiti Dam to San Antonio, New Mexico (SSPA and NMISC, April 2005; SSPA and NMISC, March 2006; SSPA and NMISC, April 2007). The riparian models improve our ability to assess shallow groundwater conditions important to water supply reliability in specific river reaches and to evaluate the feasibility of habitat restoration strategies.

This work was performed under Fiscal Year 2007 (FY07) funding from the Middle Rio Grande Endangered Species Act Collaborative Program (ESA Collaborative Program) and the New Mexico Interstate Stream Commission (NMISC), and represents the continuation of a project initiated under Fiscal Year 2003 and Fiscal Year 2004 funding from these entities. Cochiti reach model development, undertaken in 2005 and 2006, was funded by the U.S. Army Corps of Engineers and the New Mexico Interstate Stream Commission.

Principal investigators for this project were Deborah L. Hathaway of S.S. Papadopulos & Associates, Inc. (SSPA), and Nabil Shafike of the New Mexico Interstate Stream Commission. Work was conducted by the principal investigators and SSPA team members, including Karen MacClune, Gilbert Barth, and Elizabeth Jones.

## 1.1 Project Justification

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 did 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 relationships characterized in this study will support the identification of flow levels that can help establish and maintain groundwater conditions for Southwest Willow Flycatcher (SWFL) habitat. Additionally, the riparian models can be applied to assess the water supply needs, incremental depletions and sustainability of stream restoration projects that, for example, may be designed to improve Silvery Minnow habitat under varying hydrologic or physical conditions.

The work described in this report extends the riparian model coverage provided by the six existing riparian models southward, from the north boundary of Bosque del Apache to the northern end of the Elephant Butte Reservoir delta. This region is an area where groundwater is shallow and the river has become significantly channelized by extensive salt cedar growth. Understanding the nature of shallow groundwater conditions and associated river gains and losses through seepage in response to flow events and physical conditions can greatly enhance the ability to manage the river to maintain flow continuity in key habitat areas. River gains and losses are sensitive not only to the river hydrograph through the area of interest, but also to antecedent hydrologic conditions, "regional" groundwater conditions, vegetative cover and geomorphologic influences.

### 1.2 Study Area Description

The study area for this project extends along the Rio Grande from the north boundary of Bosque del Apache to the northern end of the Elephant Butte Reservoir delta, a distance of approximately 26 river miles (Figure 1.1). The model covers the Rio Grande corridor, riverside bosque, and low flow conveyance channel. Hydrologic inflows and outflows in this area include river leakage, low flow 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. The riparian model provides a tool capable of examining the system under different flow regimes, such as low summer flows, spring runoff pulses, and average winter flows, and can be adapted to evaluate hydrologic questions related to river restoration.

### 1.3 Report Organization

The main body of this report describes development of the Bosque del Apache and Fort Craig shallow riparian zone models. Section 2 describes the resources available for model development. Section 3 describes the riparian model design. Section 4 describes historic groundwater conditions within the study area. Section 5 describes steady state model simulations and a transient analysis of the 2004 spring runoff pulse. Section 6 provides a summary and conclusions. Detailed technical material and supporting data are organized within several appendices, and include summaries of key data sets and metadata.

## 2.0 RESOURCES AVAILABLE FOR DEVELOPMENT OF RIPARIAN MODELS

Information to support the riparian model development has been compiled in the following areas:

- Existing regional groundwater model characteristics and simulation results;
- Groundwater elevations from piezometers cross-sections;
- Riverbed elevation (from the U.S. Bureau of Reclamation (USBR) 2002 Aggradation/Degradation lines);
- Gaged river flows; and,
- Riparian vegetation classification and water use characteristics.

These data are briefly described in this section. The analysis and use of these data in model development is described further in Sections 3 and 5.

### 2.1 Existing Regional Models

Several regional hydrologic models have been developed to represent various processes in the Middle Rio Grande region of New Mexico. These existing models have been developed for specific purposes, in most cases, to address hydrologic conditions on a regional scale. Selected simulation output from the regional models is utilized in this study to define boundary conditions for the riparian models. In turn, information developed from the riparian models may prove useful as feedback to the regional models to improve their representation of conditions within the floodplain. Existing regional models with relevance to this study are:

- NMISC Regional Groundwater Flow Model for the Socorro and San Marcial basins (Shafike, 2005 draft). The purpose of the model is to evaluate potential system-wide depletions that may result from changes in operation of the Low Flow Conveyance Channel (LFCC), riparian vegetation restoration projects, and riverbed aggradation. The model simulates the Rio Grande channel, the LFCC, and the main irrigation canals and drains as well as the alluvial and the Santa Fe group aquifers. The U.S. Geological Survey program MODBRANCH is used to represent the surface water/groundwater system. The surface water component is represented by solving the one-dimensional form of the continuity and momentum equations, known as Saint-Venant equation. The groundwater component is dynamically linked to the surface water component. The physical processes represented in the model are surface water routing, surface water / groundwater interaction, discharge from springs, riparian and crop depletions, groundwater withdrawals and groundwater levels. The model provides groundwater elevation, surface water flow and riparian and crop depletion. The Socorro-San Marcial Basin model is used in this study to define boundary conditions for the riparian groundwater models, i.e., identification of hydraulic heads representative of regional groundwater conditions in the aquifer adjacent to and below the riparian model domain.

- Upper Rio Grande Water Operations Model (URGWOM; U.S. Army Corps of Engineers, 2005): URGWOM is a cooperative effort between the U.S. Army Corps of Engineers, the NM ISC, the USBR, and the USGS. This model represents the operations of reservoirs and provides a routing analysis to simulate river hydrographs under a variety of management scenarios. URGWOM is not utilized in this study. However, results from application of the riparian models may provide material suitable for use in future refinement of the surface water-groundwater relationships in URGWOM.

- FLO-2D (Riada Engineering, 2007 draft): This model identifies hydraulic properties associated with in-channel flow and overbank flooding under various simulated flow conditions. FLO-2D is utilized in this study to provide river and overbank water surface elevations under various flow magnitudes, essentially, defining the boundary condition at the stream/aquifer interface. The seepage rates calculated in the riparian models will provide feedback on loss rates used in the FLO-2D analysis.

### 2.2 Groundwater Elevation Data

Groundwater data useful to this study include data from wells located in the riparian zone to the east of the river, or between the river and low flow conveyance channel on the west side of the river. Seven well transects across the riparian zone in the Socorro Basin were installed in 2003 as part of the Rio Grande Watershed Study (RGWS), funded by the U. S. Army Corps of Engineers (ACOE) and the NMISC under the Water Resources Development Act (SSPA, 2003). The wells in these transects have been monitored regularly by the NMISC, with assistance from NM Tech and SSPA, since they were installed in 2003, both through monthly manual measurements, and hourly, through the use of electronic data loggers.

Groundwater elevations from multi-level piezometers situated along transects located within the Bosque del Apache and Fort Craig model areas were used in this study. These transects are as follows:

- <u>Highway 380 Bridge (designated “HWY”):</u> This transect is located north of the Highway 380 Bridge in San Antonio, New Mexico, in an area with agricultural lands on the west side of the river. On the east side of the river is a very extensive riparian corridor (a three-mile swath of salt-cedar) extending from the river to the dead-end of the San Pedro Arroyo (this arroyo no longer connects to the Rio Grande). This transect includes wells on both the east and west sides of the river.

- South Bosque Boundary (designated "SBB"): This transect is located just downstream of the southern boundary of the Bosque del Apache National Wildlife Refuge (BdANWR), in an area of fairly dense salt cedar. This transect includes wells on both the east and west sides of the river.

- San Marcial (designated "SMC"): This transect is located just south of the San Marcial railroad bridge in an area of fairly dense salt cedar. This transect includes wells on the west side of the river only.

- South of Fort Craig (designated "SFC"): This transect is located about one river-mile north of where the power lines cross the Rio Grande. This transect includes wells on the west side of the river only.

Well lines at all four transects are oriented approximately at right angles to the Rio Grande and the LFCC, with 5 to 14 wells per line, all screened within the river alluvium. Some of the wells are nested; "A" wells are screened across the water table (typically, within the range of 5 to 20 ft below land surface); "B" wells have 5-foot screens typically placed between a depth of 40 and 55 feet below land surface. In addition, each of the transects has a single "C" well screened in the lowermost portion of the river alluvium, typically, located between 75 and 90 feet below land surface. Staff gages were additionally installed at prominent surface water features along the transects, typically including the Rio Grande, the LFCC and nearby major canals (SSPA, 2003).

Table 2.1 lists completion details for the monitoring wells in these transects. Well locations relative to the Bosque del Apache and Fort Craig model boundaries are shown on Figure 2.1. Figure 2.2 a-d provides information on the geologic materials encountered at the wells and their depths along cross-sections at each of the four locations. Hydrographs for the monitoring wells, including data from continuous recorders and manual measurements, are provided in Appendix C.

### 2.3 Land Surface Elevation Data

Land surface elevations (for the top of layer 1) for the Bosque del Apache and Fort Craig models were averaged to grid resolution from USGS 10-meter DEMs. A datum correction was applied to convert from NGVD29 to NAVD88 vertical reference datum. A comparison of these

DEM-based land surface elevations (averaged for a given model cell) with surveyed well elevations at specific piezometers along the transects suggests that the 10-meter DEM land surface elevations may be biased low, on the order of a couple to a few feet. Bias may increase southward. If higher resolution DEMs are developed for these reaches in the future, it is recommended that land surface elevations be updated.

### 2.4 Drain Bed Elevation Data

Drain bed survey data were obtained from the NMISC and used to characterize bed elevations in the LFCC. Surveyed drain bed elevations were associated with the LFCC linear feature. Model grid cells were then intersected with the LFCC, and a linear interpolation was applied to calculate elevations at the mid-point of each of the intersected model grid cells.

Interpolated drain bed elevations were compared with assigned land surface elevation for each cell traversed by the LFCC; results are shown in Figure 2.3. Within the Bosque del Apache model, LFCC bottom elevation is generally 10 to 15 feet below land surface; average depth over the length of the model is just under 10 feet. However, at the southern end of the model, land surface elevations for the model cells containing the LFCC drop to equal the LFCC bottom elevation at two locations.

Within the Fort Craig model, LFCC bottom elevations average slightly over 8 feet below land surface elevation. However, within individual cells, land surface elevation ranges from 24 feet above to 3.5 feet below LFCC bottom elevations. In particular, at the southern end of the model LFCC bottom elevations are near or above land surface elevation from model row 210 south.

Model areas where the LFCC bottom elevation is near or above land surface elevation are likely primarily an artifact of DEM coarseness and the low-bias in land surface elevation identified above. There may also be areas where the LFCC, bounded by its levees, is indeed above average land surface elevation. Care should be taken in interpreting model results in these areas.

### 2.5 Riverbed Elevation

Riverbed elevations along channel cross-sections were obtained from the 2002 USBR Aggradation/Degradation lines (Ag/Deg lines). The Ag/Deg lines are based on 2002 aerial photography, photo-interpreted by the USBR. Ag/Deg line riverbed elevations are reportedly estimated from the average flow depths at the time of the photography (estimated flow depths at the time of the photography are subtracted from the water-surface elevation to produce an estimated average bed elevation). The interpretation assumes a flat river bottom for all areas inundated at the time of the photography. The minimum elevation along the cross-section (i.e. the average river bed elevation assigned to all inundated areas) for each Ag/Deg line was extracted from the dataset for use as riverbed elevation within the riparian models. Linear interpolation, followed by smoothing, was applied to calculate the riverbed elevation for each riparian model grid cell from the Ag/Deg-based riverbed elevation.

Horizontal locations in the Ag/Deg data were determined to be referenced to the WGS84 (NAD83) horizontal datum. Vertical datum information, however, was not located. A comparison between calculated riparian model river bottom elevations and river bottom elevations extracted from the FLO-2D files supports the conclusion that the two data sets are referenced to the same datum. FLO-2D elevations are given in NAVD88 (Riada Engineering, 2007); therefore, it is inferred that 2002 USBR Ag/Deg elevations are referenced to NAVD88.

As for the LFCC, interpolated river bed elevations were compared with assigned land surface elevation for each cell traversed by the river; results are shown in Figure 2.4. Within the Bosque del Apache model, river bottom elevation is on average 0.6 feet below land surface. However, at the southern end of the model, river bottom elevations for the model cells containing the river rise to as high as 7.7 feet above land surface elevation. Within the Fort Craig model, river bottom elevations are, on average, 4 feet above land surface elevation. Some of these differences may be attributable to DEM coarseness and the low bias noted above. Groundwater model results, in terms of elevation, will not be highly sensitive to inaccuracy in the DEM-based land surface elevation. However, calculations of depth to groundwater would be impacted and should be evaluated with caution until higher resolution DEMs can be obtained[1].

### 2.6 Riparian Vegetation Classification

Riparian communities in the study reach were identified based on two available vegetation classification coverages:

- Vegetation mapping coverages created as a part of the Upper Rio Grande Water Operations Review and Environmental Impact Statement (URGWOPS) (USBR, 2004); and,
- IKONOS riparian vegetation classification coverages (Strech and Matthews, 2001).

URGWOPS vegetation mapping coverages for the Albuquerque and Isleta to Elephant Butte Reaches were developed as part of a GIS-based inventory and mapping project conducted for the ESA Collaborative Program and URGWOPS. The URGWOPS vegetation mapping was used as the primary vegetation coverage in constructing the riparian model. In the URGWOPS coverage, vegetation is classified into thirty-three community types and structure classes using a modified version of the Hink and Ohmart (1984) alphanumeric descriptive code.

For areas of the model grid that were not covered by the URGWOPS vegetation coverages, the IKONOS riparian vegetation classification was used. The IKONOS vegetation classification is based on IKONOS color-infrared satellite data that was collected during the summer of 2000 for joint use by the Middle Rio Grande Conservancy District (MRGCD) and NMISC. These data were used to develop a standardized vegetation classification system for the Middle Rio Grande.

### 2.7 Riparian Evapotranspiration Rates

Research on riparian ET rates, within the Middle Rio Grande region and elsewhere, suggests that riparian ET is a complicated parameter; rates may vary depending on numerous factors, including but not limited to vegetation composition and density, groundwater depth,

[1] Also of concern is the potential over-estimation of overbank areas and overbank flooding using a DEM product that underestimates land surface. Such a bias may be implicit in the FLO-2D results that are used to define boundary conditions in this model. Significant model refinement may be possible if higher resolution land surface elevations are obtained in the future.

weather conditions, and season. Figures 2.3a and b illustrate annual and monthly riparian ET data collected at different tower locations in the Middle Rio Grande valley for the period from year 2000 to year 2005 (C. Dahm and J. Cleverly, University of New Mexico). These data demonstrate the spatial and temporal variability of ET measurements in the Middle Rio Grande region and illustrate the difficulty in making general inferences concerning water use by riparian plant class.

Figure 2.6 provides a depiction of ET rates and groundwater depths during 2003 at a site with salt cedar in the Bosque del Apache NWR. ET continued through the summer as groundwater levels dropped, suggesting that ET is not strongly dependent on groundwater depth in these ranges (1.75 to 3.75 meters below land surface). However, some observations during dry periods suggest that cottonwood may be more sensitive to water level changes. At a site south of Los Lunas in 2003, during a period when groundwater levels declined from 3 to 7 feet below ground surface, cottonwood trees appeared to be stressed. Additional data is needed to fully characterize the change in ET as a function of groundwater depth.

### 2.8 Open Water Evaporation Rates

Open water evaporation rates were based on daily pan evaporation measurements taken by the USBR at Elephant Butte Dam during 2004, 2005 and 2006, corrected by a factor of 0.7 to account for increased heating and evaporative losses from the pan as compared to an open water surface. The measurement location is approximately 32 miles south of the bottom end of the Fort Craig reach. Data were used to derive average monthly evaporation rates; derived rates are shown in Table 2.2 and Figure 2.7.

### 2.9 River Seepage Estimates

The reach of the Middle Rio Grande from the Highway 380 Bridge to Fort Craig is, in general, a losing reach. Exchanges between the river, LFCC, and groundwater in this reach were measured on several occasions during 2000 and 2001 (SSPA, 2001; SSPA, 2002). Seepage data for the river and LFCC sub-reaches lying within the model area are presented in Tables 2.3a and 2.3b.

In the reach from the Highway 380 Bridge to the South Boundary of the BdANWR, losses from the river range from 4 to 12 cfs per mile. Losses between Highway 380 and the

North Boundary of the BdA diminish, or turn into small gains, during the post-irrigation season (winter). In the remaining reaches, between South Boundary BdANWR and Fort Craig, river losses measured during the irrigation season are lower, ranging from 1 to 5 cfs. However, during a winter season measurement event, measured losses were higher (9.5 cfs per mile) between South Boundary BdANWR and San Marcial, but a gain of 1.4 cfs was measured between San Marcial and Fort Craig.

Low Flow Conveyance Channel seepage estimates are shown on Table 2.3b; average gains/losses range from losses of 1.8 cfs per mile to gains of 4.1 cfs per mile. The greatest gains between Highway 380 and the Corral were found between the north and south boundaries of Bosque del Apache. Losses were found between Fort Craig and the Corral. The magnitude of gain or loss is related to the groundwater level with respect to drain elevation, and irrigation season activities.

# 3.0 RIPARIAN MODEL DEVELOPMENT

The Bosque del Apache and Fort Craig riparian groundwater models were developed in MODFLOW 2000 (Harbaugh et al., 2000). The models utilize output from the Middle Rio Grande FLO-2D Flood Routing Model (Riada Engineering, 2007) to specify transient boundary conditions such as wetted area and water depth at the river/aquifer interface. A very fine mesh is used for the model to allow for detailed assessment of riparian groundwater conditions and surface water-groundwater exchanges. The models represents three layers within the alluvial zone (upper 80 feet), to allow for detailed simulation of vertical gradients, and a fourth layer in the Upper Santa Fe, to allow for modeling exchanges with the deeper aquifer.

## 3.1 Model Grid

The Bosque del Apache and Fort Craig models employ grids with cells 125 feet wide and 250 feet long, oriented lengthwise along the river. Both model grids are rotated 25 degrees clockwise of north, so that, on average, the grid cell long-axes parallel the Rio Grande. The Bosque del Apache model is 192 cells wide by 356 cells long, and overlaps the Socorro riparian model, developed in a previous study (SSPA and NMISC, 2006), by roughly three miles. The Fort Craig model is 194 cells wide by 266 cells long, and overlaps the Bosque del Apache model by roughly three miles. For both models, the large overlap is driven by the location of observation well transects and the desire to avoid locating north-south model boundaries too close to observation data.

## 3.2 Model Layers

Both models are discretized in the vertical direction into four layers. The top three layers represent the Rio Grande alluvium and the fourth layer represents the uppermost portion of the Santa Fe Group. Model layer thicknesses directly below the bed of the Rio Grande are 20 feet, 30 feet, 30 feet, 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, and Layer 4 is 100 feet thick throughout. These layer thicknesses are identical to those used in the northern six models; examinations of well logs and test data in the Bosque del Apache and Fort Craig reaches suggest that the vertical discretization used in the six existing riparian models also was suitable for the

Rio Grande valley within the Socorro Basin. For both the Bosque del Apache and Fort Craig models, model layers 1, 2 and 3 correspond to layer 1 of the Socorro regional model; model layer 4 corresponds to the upper portion of layer 2 of the Socorro regional model.

## 3.3 Boundary Conditions

The active model cells were designated to include the Rio Grande corridor and bordering riparian bosque, bounded on the west by the Low Flow Conveyance Channel and on the east primarily by barren lands. This resulted in long, thin active model areas. Boundary conditions providing significant control on the shallow riparian groundwater elevations include regional (lateral and deeper) groundwater elevations, and LFCC and river channel stage. Four MODFLOW packages were used to specify boundary conditions within the model. The River Package (RIV, or, river package) was used to address the two types of surface water conditions within the model: in-channel Rio Grande stage and overbank Rio Grande water elevation. The Stream Package (STR, or stream package) was used to represent LFCC water conditions. The Riparian Package (RIP, or, riparian package; Maddock and Baird, 2004) was used to represent riparian vegetation classes and evapotranspiration rates as described in section 3.5. Model boundaries in model layers 1 through 4 were represented using the General Head Boundary Package (GHB, or, general head boundary package); this package was used to set lateral boundaries in model layers 1 through 4, and the vertical boundary in layer 4. The handling of each of these boundary types is described below.

### 3.3.1 Rio Grande

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. A set of river boundary conditions is desired that spans a wide range of potential flow conditions. After inspection of the range of historic flows, 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, which represents the Rio Grande boundary condition for the groundwater models. The details of this procedure are described below.

#### 3.3.1.1 MODFLOW River Package

The river package is used to simulate the river boundary condition in the riparian groundwater models. This package is well-suited for this application, as it allows for simulation of surface water-groundwater exchanges given a set of specified river conditions. The river conditions specified in this package include, for each model cell traversed by the river, the elevation of the channel bottom, the elevation of the water surface in the channel, and a conductance term. This package is also used in these models to specify characteristics of flooded overbank areas. The conductance term incorporates assumptions regarding vertical hydraulic conductivity, bed thickness, and the wetted area within the model cell.

Surface-water flow routing in the Rio Grande system is not simulated in the RIV package. Routing is independently simulated with FLO-2D. The FLO-2D output is used to describe the river condition in terms of stage and basic channel geometry under the simulated flow scenarios.

A library of RIV package input files was prepared corresponding to the selected flow magnitudes. The RIV files include specifications for in-channel flow and overbank flow. For a given model scenario, one or more RIV input files may be used. For steady-state analysis, the RIV file corresponding to the flow magnitude of interest is selected. For transient analysis, for example to simulate a spring run-off period, the actual hydrograph is transformed to a step-function hydrograph using flow magnitudes for which individual RIV files have been developed. The RIV files are then sequenced and utilized accordingly within model stress periods defined by changes in the step-function hydrograph. The adaptation of actual flow hydrographs to step-function hydrographs is shown on Figure 3.1, which illustrates daily flow and the step-function that could be used to simulate the sequence of flow conditions preceding and during the run-off season in 2004.

#### 3.3.1.2 River Channel Representation in River Package

For the Bosque del Apache and Fort Craig riparian models, in-channel river cells were delineated based on visual identification of the active river channel (i.e. where vegetation is at a minimum), using 2005 CIR orthophotos. For each in-channel cell, river bottom elevation, water surface elevation, and conductance are specified.

The river bottom elevation (designated RBOT in the RIV Package) is based on interpolation between 2002 USBR Ag/Deg cross-section minima, available approximately every 500 feet along the river. For each Ag/Deg line, the minimum elevation was assigned to the river centerline at the point at which it was intersected by the Ag/Deg line. Values were then interpolated along the centerline, smoothed, and river bottom elevations were assigned to all riparian model cells intersected by the river centerline. Channel cells were then grouped by row, and equal river bottom elevations assigned to all in-channel cells within the row.

The water surface elevation is determined from FLO-2D flood routing model results for each selected flow magnitude. FLO-2D provides an output file, HYCHAN.OUT, which lists the channel flow hydraulics including elevation, flow depth, velocity, and discharge by FLO-2D grid element. Each riparian model in-channel cell is associated with the nearest FLO-2D channel element, and FLO-2D water depths corresponding to a given flow level were assigned to riparian model in-channel cells for use in river package construction.[1] Details of this procedure are provided in metadata within Appendix A.

Because flow does not necessarily occur over the entire riparian model channel width (bank to bank) at each library flow, 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 (*Top Width / Max Top Width*). This correction factor is implemented within the definition of the river conductance (discussed

[1] The utilization of FLO-2D derived water depth as opposed to FLO-2D derived water elevation provides some advantage in handling minor differences in channel elevations associated with the different model grids and supports a closer match in flow volume between the two models. However, due to differences in model discretization and interpolation techniques, locally, this method can result in the assignment of a downstream in-channel water surface elevation greater than the upstream surface elevations. This is not considered problematic due to the relatively small differences and because the River Package (as opposed to the Stream Package) does not compute in-channel flow.

below), a term used by the RIV Package that incorporates the channel width, along with channel bed properties.

Bed conductance for in-channel cells was calculated using the following equation:

$$C = \frac{L * W * \left( {TopWidth}/{MaxTopWidth} \right) * K_v}{M} \qquad \text{Equation 3.1}$$

where:

$C$ is river bed conductance (ft$^2$ /day);
$L$ is length of river within the given cell (set equal to the length of the cell, 250 ft);
$W$ is width of river within the given cell (set equal to the width of the cell, 125 ft);
*TopWidth* is the top width of the river channel under the given flow conditions (FLO-2D output);
*MaxTopWidth* is the maximum width of the river channel (FLO-2D Top Width from the 10,000 cfs flow scenario);
$K_v$ is river bed vertical hydraulic conductivity (initially set at 1 ft/day);
$M$ is river bed thickness (initially set at 1 ft).

#### 3.3.1.3 Overbank Flooding Representation in River Package

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. Overbank flows were found in FLO-2D model simulations for flows of 2,000 cfs and greater. For these flows, overbank water depths were calculated from the FLO-2D model output by adding water depth from the FLO-2D output file DEPTH.OUT to riparian model floodplain surface elevation. Where the depth value reported in DEPTH.OUT reflects an in-channel water depth, depth was adjusted by the difference between land-surface elevation and river bottom elevation for the given FLO-2D cell.

FLO-2D over-bank water depths were superimposed on the riparian model grid, flooding was eliminated from LFCC cells, and for the remaining cells, 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 depth for the flooded portion of each riparian cell. Riparian model overbank cell conductance was scaled by the percentage of the cell flooded. Conductance was calculated using the following equation:

$$C = \frac{L * W * K_v}{M} * \frac{PerCov}{100} \qquad \text{Equation 3.2}$$

where:

$C$ is the flooded model cell conductance (ft$^2$ /day);
$L$ is length cell, 250 ft;
$W$ is width of cell, 125 ft;
$K_v$ is the floodplain surface vertical hydraulic conductivity (initially set at 1 ft/day);
$PerCov$ is the percentage of the riparian cell covered by flooded FLO-2D cells;
$M$ is the presumed bed thickness (initially set at 1 ft).

### 3.3.2 Low Flow Conveyance Channel

The Low Flow Conveyance Channel, which determines the model layer 1 western boundary for all of the Bosque del Apache model and most of the Fort Craig model, was represented using the MODFLOW Stream (STR) Package. Within each model, the LFCC was designated as a stream segment. The stream segments consist of multiple stream reaches, generally corresponding to model cells intersected by the stream segments. However, in some cases, sections of LFCC in two adjacent lateral cells were aggregated into one model cell to simplify the spatial representation of the LFCC. Such aggregation was handled in a manner such that the overall LFCC distance and conductive capacity were preserved.

The STR package was set up to calculate LFCC stage. Drainbed conductance was calculated using the following equation:

$$C = \frac{L * W * K_v}{M} \qquad \text{Equation 3.3}$$

where:

$C$ is riverside drain bed conductance (ft$^2$/day);
$L$ is length of the drain within the given cell (ft);
$W$ is width of the drain within the given cell (set equal to 30 ft);
$K_v$ is the drain bed vertical hydraulic conductivity (initially set at 1 ft/day);
$M$ is the drain bed thickness (initially set at 1 ft).

### 3.3.3 Lateral Boundary Conditions

The GHB Package was used to specify boundary conditions at the sides and the bottom of the active model domain. Through the GHB Package, head-dependent boundaries are specified that allow for the exchange of water between the active model domain and the surrounding area. The GHB Package requires the specification of a head at a given distance, and a conductance factor that reflects the hydraulic conductivity, the distance between the boundary cell and the location of the specified head, and the cross-sectional area through which the head-dependent flow occurs. The input to the GHB Package was developed in accordance with attributes controlling lateral flow to/from each model layer and for vertical flow through the bottom layer. Lateral flow was represented in the GHB Package at all perimeter cells in layers 1 through 4, except where layer 1 perimeter cells contain the LFCC or overbank flooding (flow dependent GHB packages were constructed to address flow-dependent overbank flooding conditions). Vertical flow, representing exchange with the underlying Santa Fe Formation, was set up with the GHB package to occur through the sides or bottom of layer 4 model cells.

For the Bosque del Apache and Fort Craig models, simulated groundwater elevations were extracted from the Socorro regional groundwater model for use as GHB heads. Socorro regional model heads were interpolated to the scale of the riparian model grid cells. Socorro regional model water table heads were assigned to riparian model layers 1 through 3 GHB cells to represent lateral flow. Socorro regional model layer 2 elevations were used in all active riparian groundwater model layer 4 cells to represent vertical interaction with the underlying Santa Fe Formation. Boundary heads assigned to the riparian model GHB cells were selected from the interpolated regional model data at a specified distance outside the riparian model (see Appendix A).

Riparian model GHB cell conductances were computed using the distance between the centroid of the riparian model GHB cell and location of the interpolated regional model head selected as boundary condition, in combination with aquifer properties (discussed in Section 3.4), and cross-sectional area perpendicular to the direction of flow. The specifics of these calculations are given in the GHB metadata presented in Appendix A.

## 3.4 Initial Hydraulic Properties

### 3.4.1 Layer Type Specification

For model development, all model layers were assigned a layer-type flag of zero (layer-type zero), meaning that transmissivity is fixed (i.e., does not change as a function of head). Additionally, with this layer type designation, there is no provision for storage conversion should a layer change from confined to unconfined. The upper model layer is modeled with a storage parameter representing specific yield (i.e., yield from storage under unconfined conditions) and the underlying layers are modeled with a confined condition storage coefficient (i.e., changes in storage from pore volume and water compressibility due to head changes below the uppermost, or, water table, layer). While the layer-type zero flag is conventionally applied to simulation of confined aquifers, there are certain advantages to utilizing this approach for a system including an unconfined layer, where associated approximations are acceptable. The key advantage of this approach is improved ability to attain convergence of numerical solutions, and avoidance of non-linearity in the solution of groundwater equations due to adjustment of transmissivity with changes in hydraulic head. Particularly with simulations involving detailed representation of surface water networks, the facilitation of numerical solution through elimination of non-essential non-linearity is beneficial during model development.

The utilization of layer-type zero for the upper unconfined layer does not permit the re-calculation of transmissivity during a simulation as head varies. This approximation is often considered acceptable when the change in saturated thickness during the model simulation is less than or equal 10 percent; however, the range of acceptability is dependent on model sensitivity to hydraulic parameters and modeling goals. This approximation is examined for reasonableness in model testing.

With respect to the specification of storage properties, when using layer-type zero, a storage coefficient is calculated by multiplying specific storage by the layer thickness. For the upper layer, which is intended to be simulated with a water-table storage property, this is accomplished by assigning a specific storage parameter equal to the desired value of specific yield divided by the layer thickness.

### 3.4.2 Horizontal Hydraulic Conductivity

Initial values for riparian model hydraulic parameters (vertical and horizontal hydraulic conductivity, specific storage, and specific yield) were assigned based primarily on inspection of well logs and aquifer test data (SSPA, 2003; SSPA, 2004). Layer 1 was assigned a constant hydraulic conductivity of 15 feet per day, layer 2 a constant conductivity of 60 feet per day, and layer 3 a constant conductivity of 175 feet per day. Layer 4 was assigned a constant conductivity of 1 foot per day, primarily based on the Socorro regional groundwater model parameterization.

### 3.4.3 Vertical Hydraulic Conductivity

Vertical hydraulic conductivity is modeled as a fixed percentage of horizontal hydraulic conductivity in this model phase. The assumed ratio of horizontal to vertical hydraulic conductivity is 20:1 for layer 1, 2:1 for layers 2 and 3, and 150:1 for layer 4 and used in the conductance terms of layer 4 GHB cells representing interaction with the Santa Fe Formation. The increased ratio in layer 4 represents the lower vertical hydraulic conductivity of the underlying Santa Fe Formation.

MODFLOW 2000 uses the ratios of horizontal to vertical conductivity to create vertical hydraulic conductivity (*VK*) by dividing the horizontal hydraulic conductivity (*K*) by the ratio (*VKA*). Vertical conductance in a cell ($CV_k$) is determined by multiplying horizontal cell-face area times VK and dividing by the cell thickness. Conductance ($CV_{k + ½}$) between two vertically adjoining cells is calculated by determining the equivalent conductance of two half cells in series: the bottom half of the upper cell and the top half of the lower cell, where the *k* subscript refers to the upper cell, *k+1* indicates the lower cell, and *k+1/2* indicates the conductance between cells *k* and *k+1*:

$$CV_{k+\frac{1}{2}} = \frac{Area}{\dfrac{\frac{1}{2}Thickness_k}{VK_k} + \dfrac{\frac{1}{2}Thickness_{k+1}}{VK_{k+1}}}$$

### 3.4.4 Storage Properties

Specific yield in the uppermost (water-table) layer of the valley alluvium is represented in the models as 0.2 (adopting the value utilized in McAda and Barroll, 2002). This value reflects the storage associated with the filling or draining of inter-granular voids at the water table, located within model layer 1. Because this layer is specified in MODFLOW as layer type 0, a "dummy" specific storage is utilized which when multiplied by the layer thickness, results in a storage parameter of 0.2.

In underlying layers, where the full layer thickness remains saturated and no water table is present, storage is limited to changes in pore volume due to aquifer compressibility and changes in water density associated with head changes. Therefore, the storage coefficient for layers 2, 3 and 4 reflects a specific storage on the order of what would be typical for confined conditions within unconsolidated alluvial material. Initially specified as $1 \times 10^{-5}$ ($ft^{-1}$), the specific storage is then multiplied by the layer thickness to obtain a value for storage coefficient. The layer type and parameter assignments for layers 2, 3 and 4 are made under the assumption that layer 1 does not become dewatered; this assumption is justified given the hydraulic control represented by river and drains within the active model area. However, should localized conditions or focused scenarios indicate otherwise in model applications, these attributes could be modified.

## 3.5 <u>Riparian Evapotranspiration</u>

Water depletions in the riparian corridor occur through evaporation from open water and wet soil and through ET from riparian vegetation. The simulation of these processes is described in this section.

### 3.5.1 Specifying Vegetation Coverage within Active Model Grid

Riparian communities in the study reach were identified based on available URGWOPS and IKONOS GIS vegetation classification coverages (see Section 2.5). The URGWOPS vegetation classification was used as the primary coverage for development of the riparian models. The 33 vegetation classes in the URGWOPS classification were grouped into eight general core groups of plants with similar ET rates. The core groups used were:

- Cottonwood Pure (Cottonwood with little or no understory; existing understory is composed predominately of native plants)
- Cottonwood Mixed (Cottonwood with well developed understory; understory contains a significant proportion of non-native plants)
- Russian Olive
- Salt Cedar
- Riparian Woodland
- Marsh
- Bare Land
- Open Water

The Open Water group was further subdivided into in-channel open water cells and non-in-channel open water cells. Vegetation coverage within in-channel river cells was set to 100% in-channel open water. The ET rate for the in-channel Open Water is currently set to zero since the FLO-2D model simulation accounts for evaporation from the river and overbank water surfaces. However, a separate in-channel Open Water sub-group was included for flexibility, to allow the possibility of setting different evaporation rates in future runs.

The URGWOPS categories contained within each of these core groups are listed in Table 3.1. The percentage occurrence of each core group was determined for each model cell and included in the RIP package. For model cells with less than 100% coverage by URGWOPS vegetation classification data, the remaining cell area was specified as bare land based on visual inspection of the unrepresented areas using available aerial photography. The exception was at the lower end of the Fort Craig model, south of the power lines, where the URGWOPS data ends. In this area, IKONOS data were used to designate vegetation coverage. The IKONOS color-infrared satellite data was transformed to point features and the pixel-values were grouped into the same core groups used for the URGWOPS coverage (Table 3.1). For the Bosque del Apache and Fort Craig models, percentage vegetation coverage by category is listed in Table 3.2.

### 3.5.2 Specifying Land Surface Elevation within the RIP Package

For each model cell represented in the RIP package, a land surface elevation is specified. For all cells, land surface elevation, as described in Section 3.2, was used.

### 3.5.3 Development of ET Rate Curves for use in MODFLOW RIP Package

For each of the specified vegetation categories, a riparian ET rate with depth curve was developed based on best available information. The curves were used in the RIP Package (Maddock and Baird, 2004) to simulate riparian ET as a function of water table depth. In applying the models to specific restoration or water conveyance scenarios, the assumed ET rates should be assessed for applicability to that scenario and modified as appropriate.

The assumed maximum ET rate for each of the core vegetation groups is listed in Table 3.3. ET curves used in the model are shown in Figure 3.2; five unique curves were developed to represent the vegetation classes used. For this location, for this phase of model development a maximum annual ET rate of 3.8 feet per year is assumed for native cottonwood, 4.2 feet per year is assumed for cottonwood with a dense understory of non-native plants, and 3.6 feet per year is assumed for salt cedar. The actual ET rate is based on many factors and may vary from the assumed rates. To address cases where the water table rises up to or above the land surface, resulting in open water surfaces, maximum plant ET rate was continued to the land surface and above for the salt cedar plant group; for cottonwood native, cottonwood with non-natives, Russian Olive and Riparian Woodland, ET rate was reduced to 90% of maximum at land surface. These values are considered to be reasonable estimates of flooded land ET for these under-canopy areas. Large areas of exposed open water throughout the Middle Rio Grande region are generally assigned an open water evaporation rate of about 5 feet per year (ET Toolbox, USBR, 2003). However, under dense foliage, open-water evaporation rates would likely be reduced; for site-specific applications this should be reviewed, and revised if needed.

A single curve was used to represent Bare Land, Unknown Vegetation, and non-in-channel Open Water. The ET rate curve for these groups rises from 0 to 1 foot per year when the groundwater level is between 1 foot and a half foot in depth, and then rises to 5 feet per year, representative of open water, when the water table surface is between a half foot deep and land surface. The majority of the lands designated Unknown Vegetation lie at the edges of the model domain where IKONOS data is lacking; visual inspection of aerial photography suggests these areas are bare land or grassland. Both grassland and bare land will draw water from the groundwater system only when water table levels are near land surface; when the water table is at land surface, they will experience open water evaporation. The non-in-channel open water cells were assigned the bare land/grassland curve in recognition that, regardless of whether they appear as open water in aerial photography, we do not want to be removing water from the water table below these areas via evaporation unless the water table is at or near land surface. It is possible that open water surfaces seen in the aerial photography are the result of ponding on top of barrier layers, either man-made or natural.

For the Marsh category, which has a maximum ET rate of 6 feet per year, the ET rate at land surface and above is set at 5 feet per year, a value more representative of open water evaporation rates.

#### 3.5.4 Development of Temporally Varying MODFLOW RIP Package

Riparian evapotranspiration and open water evaporation 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.

To allow for temporally varying simulation of evapotranspiration using the RIP package, a set of 12 monthly RIP packages were prepared. For each of the monthly packages, the percentage plant coverage within each cell by each plant sub-group was varied as a function of time within the growing season. For vegetation, a hypothetical curve describing the variation of evapotranspiration with time was developed based on monthly ET rates averaged over 5 years for salt cedar, cottonwood and Russian olive (2000-2004 UNM data, Sevilleta LTER website). The average monthly ET rate, as a percentage of total annual evapotranspiration, for each of the five vegetation categories, and the hypothetical curve extracted from them, are shown in Figure 3.3. The average monthly ET rates were used to calculate monthly evapotranspiration weighting factors, and the weighting factor used to scale percentage plant sub-group coverage for each vegetation sub-group within each active model cell. The same weighting factors were used for each of the vegetation categories. Weighting factors ranged from 0 to 2.4, reflecting the winter periods (October to April) with no transpiration, and the very high evapotranspiration rates during June and July. The percentage coverage of each cell by each plant sub-group was left unchanged when the average monthly ET rate was equal to 1/12$^{th}$ (8.33%) of the annual ET rate. As a result, from October to April, when the hypothetical curve monthly ET rates are less than

8.33% of the annual ET rate, percent coverage was scaled down; from May through September, when the hypothetical curve monthly ET rates are greater than 8.33% of the annual ET rate, percent coverage was scaled up.

For open water, the same methodology as described above was used to implement the open water evaporation curve shown in Figure 2.5. For open water, weighting factors ranged from 0.37 to 1.77, reflecting low evaporation rates in winter and high evaporation rates in summer.

## 4.0 GROUNDWATER ELEVATION CONDITIONS

The Bosque del Apache and Fort Craig model domains fall within the Socorro structural basin (Socorro Basin). Groundwater elevations within the model domains vary primarily as a function of river flow. There is little to no groundwater pumping in the area, little irrigation, and no evidence that groundwater today behaves significantly differently than it has since the installation of the LFCC. Spatial differences in groundwater elevations and river gains/losses are influenced by channel and land surface elevations, as well as vegetative coverage. Temporal differences in groundwater elevations and river gains/losses are influenced by seasonal and operational fluctuations in the river.

Groundwater elevation data for the four water-level monitoring transects within the model study area (Section 2.2) were reviewed. This section describes and illustrates shallow groundwater elevation conditions of the aquifer within and outside of the riparian corridor from the Highway 380 bridge to the Elephant Butte Reservoir delta just south of the power lines. Conditions within the riparian corridor have obvious relevance to this study; conditions nearby but outside of the riparian corridor are also of interest as they reflect regional conditions that impact the riparian corridor and are relevant to the specification of boundary conditions in the riparian groundwater models.

### 4.1 River Conditions

The Ft. Craig reach of the Middle Rio Grande constitutes the upper portion of the delta of the Elephant Butte Reservoir, parts of which are active delta when reservoir levels are high. The Bosque del Apache reach, located upstream of the Ft. Craig reach and adjacent to the Bosque del Apache, is an area within which wildlife and habitat preservation is the dominant land use. The proximity of these reaches to the reservoir delta has resulted in sediment accumulation over the past century, which has raised (aggraded) the riverbed. This situation has been aggravated by increases in sediment load from the Rio Puerco, as this tributary has incised over approximately the same time period (MEI, 2002: after Rittenhouse, 1944; Happ, 1948; and Elliott, 1979)[3]. The Highway 380 transect in San Antonio is at a location that is fairly neutral – over the past half century, riverbed degradation has occurred upstream of this location and aggradation has

[3] Very recently, and in response to pilot channel construction activities, a reversal of this trend may be occurring.

occurred downstream of this location. The amount of aggradation increases downstream, with the highest level of aggradation occurring at the South of Fort Craig transect location. At the South Boundary of Bosque del Apache, San Marcial, and South of Fort Craig transects, the bed elevation has increased 10 to 15 feet since 1962; one to two feet of that aggradation has occurred since 1987 (MEI, 2002).

River widths in this reach range from approximately 200 feet up to 1,500 feet. Although river widths in this reach tend to be larger than in most reaches of the Middle Rio Grande, the well transects being monitored are all installed at relatively narrow spots in the river. Due to the elevated river bed, overbanking is common in this reach when flows exceed 3,000 cfs. At flows over 5,000 cfs, extensive overbanking occurs throughout the reach.

The river system in this reach consists of the main river channel, referred to as the “floodway”, and the Low Flow Conveyance Channel (LFCC), which parallels the river on the river’s west side. From 1959 through 1985, the LFCC was used to convey all flows up to 2,000 cubic feet per second (cfs), and the floodway only conveyed water when flows were above this amount. Beginning in 1985, due to channel and reservoir conditions, flow was no longer diverted into the LFCC at its head. However, the LFCC still collects water from both the east and the west, functioning as a drain with its invert elevation lower than the bed elevation of the river.

During a period of years with high water levels in the reservoir, an extensive delta developed in the upper reservoir area. When reservoir levels subsequently fell, the river was not well-connected to the reservoir. In recent years, the U. S. Bureau of Reclamation and the New Mexico Interstate Stream Commission performed significant earthworks to reconnect the river to the Elephant Butte Reservoir. With this improvement in river flow conditions, some channel down-cutting as far upstream as South of Fort Craig may have occurred.

### 4.2 Groundwater Conditions

A series of figures are provided to illustrate groundwater elevation conditions at each of the four monitoring transects: Highway 380 (Figure 4.1 A-C), South Boundary Bosque del Apache (Figure 4.2 A-C), San Marcial (Figure 4.3 A-C) and South of Fort Craig (Figure 4.4 A-C), in each of four seasons of the years 2004, 2005, and second half-2006 through first half-

2007[4]. The figures show a profile of groundwater elevations in the A wells, the B wells, and vertical gradients between A and B wells, where data are sufficient to calculate the gradient across the transect. The observed conditions at each transect are described below.

#### 4.2.1 Highway 380 Transect

At the Highway 380 transect (Figures 4.1A-C), horizontal head gradients on the east side of the river are generally away from the river. The gradient and head at the greatest distance from the river suggest that no significant recharge occurs to the area east of the river, other than seepage from the river. Seasonally, for example, in September-October 2006, depressions in the water table are noted in the area east of the river. These depressions may be associated with riparian water use – such a depression would be dampened in subsequent seasons, either as they equilibrate with conditions further east (that is, elevations further to the east would decline); or, as river flow increases and provides sufficient seepage to fill the depression. Resulting from the dynamics of water use to the east and seepage from the river, it is observed that the gradient very close to the river will reverse direction as a result of varying conditions.

On the west side of the river, gradients are from the river toward the LFCC (which has an average head approximately 9 feet lower than the average head in the river), and from the surrounding irrigated agricultural areas toward the Socorro Riverside Drain South and then from there toward the LFCC. Heads are highest during the spring flood pulse when the river is highest, and lowest in late-summer/early-fall when the river is dry. Heads to the west of the river are buffered by the LFCC and irrigation, though gradients close to the river may exhibit changing directions.

Heads are of similar magnitude in both the A and B wells. Vertical gradients (Figure 4.1C) are consistent with expected channel gain/loss conditions. Gradients are downward near the river during periods of flow and upward in the vicinity of the LFCC, where groundwater discharges.

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[4] These time periods were selected to illustrate conditions and trends associated with various sequences of high/low flow conditions; and, as data were deemed sufficient. As such, the "seasons" featured within the years may vary in terms of the calendar months included.

### 4.2.2 South Boundary Bosque del Apache Transect

At the SBB transect (Figures 4.2A-C), the horizontal head gradients directly east of the river are uniformly away from the river in all seasons. Further east, gradients were away from the river prior to the spring of 2005, but toward the river for several months after June 2005. This is due to extensive ponding east of the transect which resulted from the 2005 spring runoff; the ponding reversed the local horizontal flow gradients east of the river through fall 2006. To the west, horizontal head gradients are away from the river. In the vicinity of the LFCC, which has an average head approximately 10 feet lower than the average head in the river, gradients are locally toward the LFCC. Similar gradients are seen in both A and B wells. As at the HWY transect, heads are highest during the spring runoff pulse and lowest in late-summer/ early-fall.

Vertical gradients tend to be downward near the river and upward near the LFCC, with some seasonal variation depending on recharge/discharge conditions. A downward gradient is also noted to the east of the river in the area of ponding following the overbank flooding event that occurred in 2005.

### 4.2.3 San Marcial Transect

The San Marcial transect includes wells on the west side of the river only. There is about a 13 foot difference in heads between the river and LFCC at this transect, which gives rise to strong horizontal head gradients between the river and LFCC. In the A wells (Figure 4.3A), horizontal gradients are steepest between the river and LFCC, with gradients flattening further west of the LFCC. B wells (Figure 4.3B) also exhibit a gradient from the river to the LFCC. Notably, heads in the B wells lying between the LFCC and the river are significantly lower than the A well heads, perhaps reflecting fine-grained materials separating the A-interval from the B-interval observed in well logs along this transect. Nonetheless, B wells respond to changes in river conditions, as is particularly evident in examination of their hydrographs (Appendix C). Heads at the SMC transect are highest during the spring runoff pulse and lowest in the late-summer/ early-fall in both A and B wells. Vertical gradients (Figure 4.3C) are downward between the river and LFCC, neutral just east of the LFCC, and, in general, upward at the western edge of the transect.

### 4.2.4 South of Fort Craig Transect

Like the San Marcial transect, the South of Fort Craig transect includes wells on the west side of the river only. At this transect, there are no well pairs near the river. Average horizontal gradients in the "A" wells are from the river toward the LFCC. West of the LFCC, horizontal gradients generally trend west, away from both the river and the LFCC, toward non-irrigated areas. Horizontal gradients are very small beyond about 1000' from the river, and on occasion, temporarily reverse, probably due to riparian water uptake. This assumption is lent support by the vertical gradients, which are uniformly upward or near zero for all wells, but are greatest at well FTC-02 which is in the center of the riparian bosque approximately 2,000' from the river.

# 5.0 PRELIMINARY SIMULATIONS

Preliminary simulations included steady-state runs at various river flow levels, and a transient run in which the 2004 spring pulse and summer runoff season are simulated. Where available, observation well data were compared to the simulated water levels as a check on model performance.

### 5.1.1 Steady-State Simulations

Steady-state simulations were made for each of the flow magnitudes selected for the set of river package boundary conditions (100, 500, 1,500, 2,000, 3,000, 5,000, 7,000 ad 10,000 cfs). For these simulations, general head boundaries were fixed at the values previously described (Section 3.3.3). The following results were tabulated for each simulation:

- Net river seepage (from in-channel and flooded overbank cells)
- Net gains in the LFCC
- Groundwater elevations and depth below river bottom
- Vertical head differences

No historical or existing condition is strictly comparable to the results of these steady-state conditions; however, the results were reviewed for reasonableness. For example, net seepage rates for the river, river overbank, and LFCC were tabulated for each model, as shown on Tables 5.1A and B

For both models, the river loses water at all flows, and river losses increase with increasing flow. The LFCC collects water at all flows, with generally increasing gains with increasing river flows, though this relationship breaks down somewhat for river flows between 3,000 and 7,000 cfs in the Fort Craig model, as a result of the influence of overbank flows.

Overbank conditions differ significantly between models. In both models FLO-2D results indicate overbank flooding at flows of 2,000 cfs and greater. In the Bosque del Apache model, this flooding results in seepage from the overbank into the groundwater system. In the Fort Craig model, however, the model simulates groundwater at or above land surface in several areas even at flows below 2,000 cfs. Inclusion of overbank cells in the river package at flows of 2,000 cfs and higher allows the model to represent these above-land-surface water levels as river gains in areas where the FLO-2D overbank water elevation is less than the model-simulated groundwater elevation. As a result, seepage from the groundwater system into the river system overbank is simulated at all flows in which overbank cells are represented. Seepage from groundwater to the river system overbank cells increases up to river flows of 5,000 cfs. At river flows of 7,000 cfs and greater, seepage gains in the overbank begin to decrease slightly; this likely indicates that, at these flow levels, the FLO-2D overbank water elevations are greater than the model-simulated groundwater elevations in an increasing number of overbank cells, reducing overall water loss to the overbank.

Figures 5.1a and 5.1b illustrate depth to water for the 1,000 cfs flow condition. The Bosque del Apache model, shown in Figure 5.1a, appears to be simulating reasonable head values. Depth to water through most of the model is 1 to 5 feet below land surface, with the exception of along the river channel where heads rise a few feet above land surface in isolated locations. Near the south end of the model heads are over 5 feet above land surface, primarily along the river and to the east of the river. This is not surprising; in this area, the available land surface data show elevations below river bottom elevation (Figure 2.4) along the river corridor. Refined land surface elevation data are needed to improve the model simulation in this area.

The Fort Craig model, shown in Figure 5.1b, simulates water above the land surface at the 1,000 cfs flow condition in many areas. Heads along the river channel are at levels in excess of 10 feet above the simulated land surface in some local areas, and are between 5 and 9 feet above land surface in broad areas. Although some groundwater ponding at the land surface is expected in this reach, even under relatively low flow conditions, the extent of ponding shown in Figure 5.1b appears over-estimated. These results are sensitive to land surface elevation relative to river bottom elevation. For most of the Fort Craig model, river bottom elevation is above land surface elevation along the river corridor (Figure 2.4), a condition that may be more an artifact of lack of precision or accuracy of land surface elevation data rather than a realistic representation of physical conditions. Calculated groundwater depths should be considered subject to error commensurate with the unknown error in land surface elevations. Simulated groundwater elevations are considered more reliable given that they are constrained by LFCC and river bottom elevations, which have been recently surveyed. Nonetheless, as for the Bosque del Apache model, refinement of land surface elevation data are needed to improve the model simulation in this reach.

### 5.1.2 Transient Simulation

A transient simulation has been structured to examine spring runoff and summer drying of the river in 2004. To effectively capture this period, the transient simulation begins with steady-state flows of 500 cfs, representative of the flows seen from January through May 2003, followed by a transient simulation of the June 2003 through March 2004 period, to allow groundwater levels to more fully equilibrate to pre-spring 2004 levels. The June 2003 through March 2004 period includes two thunderstorm events in mid-September and early-October. The spring pulse is begun on April 2nd with 17 days of 3,000 cfs flow, 19 days of 500 cfs flow, a second pulse of 20 days of 2,000 cfs flow, and then a drop to summer 100 cfs flows on May 28th, punctuated by a brief 1,000 cfs thunderstorm runoff from July 25th to July 30th, and drying of the river beginning Sept 1st. This is summarized in Table 5.2, and shown in Figure 3.1[5].

#### 5.1.2.1 Bosque del Apache Model

Results of the transient simulation for the Bosque del Apache Model are illustrated for wells along the HWY and SBB transects on Figures 5.2 a-e. The figures show a comparison of simulated and observed groundwater elevations at several of the piezometers along the transect that had sufficient data for comparison during this period.

A good match to the transient flow conditions is shown for the wells along the HWY transect. The SBB transect shows a reasonable approximation; however, in some respects the simulated values seem high by about 1 to 3 feet. Some refinement in the land surface elevations used by FLO-2D to generate over-banked areas may be needed to improve the fit, as it appears that more water is represented in the FLO-2D based boundary condition than in fact may have occurred.

River and LFCC gains/losses occurring in this run are tabulated in Table 5.3a. Mass balance results are shown in Table 5.4a. In general, the results shown in these tables reflect expected behavior, with increases in river losses and drain gains with increases in flow. One model limitation can be noted, however; when flows drop from above 2,000 cfs to below 2,000 cfs, the simulation moves from a river package including overbank water in overbank cells to a

[5] For the zero flow condition used in the transient run, a RIV package was constructed incorporating all in-channel cells, with stage for all cells set to zero.

river package with no overbank water and no overbank cells. In effect, overbank water is instantaneously vanishing. The impact of this can be seen, for example, in river and overbank seepage and in drain gains at the end of the 7th and 9th timesteps. Both timesteps represent flows of 500 cfs. As tabulated, end-of-stress period river and drain seepages are virtually identical for both periods. However, the 7th stress period is 146 days long, following a period of 100 cfs flows, while the 9th stress period is 19 days long, following a period of 3,000 cfs flows. Given the overbank flooding represented at the 3,000 cfs flow condition, it seems unlikely that river corridor conditions would have returned to a long-term 500 cfs flow state, such as at the end of stress period 7, in just 19 days. This highlights a potential limitation of the models, depending on the application. This could be addressed via more accurate representation of the falling limb of the flood hydrograph. A series of falling-limb flow packages that allow for more gradual reduction in overbank water would allow for more realistic simulation of flood-wave recession.

#### 5.1.2.2 Ft. Craig Model

Results of the transient simulation for the Ft. Craig Model are illustrated for wells along the SMC and SFC transects on Figures 5.3 a-d. The figures show a comparison of simulated and observed groundwater elevations at several of the piezometers along the transect that had sufficient data for comparison during this period.

At both transects the simulation results show a reasonable approximation to measured conditions. However, simulated values are more responsive than observed conditions at both transects. This is particularly true for the B and C wells in the FTC transect to the east and west of the LFCC (but not to the far west of the LFCC), where measured responses are similar to the A wells, but simulated responses show up to 3 feet more amplitude than the measured values. This suggests that refinement to hydraulic properties may be warranted. However, it would be premature to refine hydraulic properties prior to addressing uncertainty in land surface elevations. Should new, higher resolution land surface elevations become available for this area, and should new FLO-2D model results based on those new data become available, simulation results for the Fort Craig riparian model should be re-evaluated using the new data.

River and LFCC gains/losses occurring in this run are tabulated in Table 5.3b. Mass balance results are shown in Table 5.4b. As for the Bosque del Apache model, the limitations inherent in modeling falling flow levels are apparent in the gains/losses and mass balance results. However, in general, results look reasonable.

## 6.0 SUMMARY AND RECOMMENDATIONS

The Bosque del Apache and Fort Craig riparian models developed for this project complete a suite of eight riparian models that cover the river and riverside drain corridor from Cochiti Dam to the northern end of the Elephant Butte Reservoir delta. These models allow for simulation of river corridor conditions under changing river, drain, vegetation, and regional groundwater conditions. These models can be used, with varying degrees of refinement, to support restoration activities such as: site selection and assessment, feasibility studies, project design, and project monitoring, operations, and maintenance; they can be used by water managers to support quantification of depletions, seepage loss, and return flow under various hypothetical conditions such as alternative water conveyance conditions or river operations scenarios.

The Bosque del Apache and Fort Craig riparian models have been constructed using the best available data, and calibrated using summer 2003 through summer 2004 flow and groundwater elevation data. Given the general correspondence in observed and simulated conditions described, the Bosque del Apache riparian model can be applied on a broad scale to address general questions related to surface water/groundwater interactions in this reach. However, additional refinement and/or calibration are recommended prior to applying the model on a sub-annual scale or to localized or site-specific management questions.

The Fort Craig model is not yet calibrated, and, until better land surface elevation data are available, it can not be fully calibrated. Subtle adjustments can be made to improve the fit between simulated and observed data, but as a predictive tool the model will remain limited.

At their current stage of development, the Bosque del Apache and Fort Craig models can be applied on a broad scale to address general questions related to river and LFCC gains and losses, and to groundwater conditions and elevations, particularly under low-flow conditions (i.e. 1,000 cfs flows and lower). The models should not be used for detailed analysis of depth-to-water or high flow scenarios without further refinement.

The next steps for model refinement for the Bosque del Apache and Fort Craig models include:

- the incorporation of higher resolution land surface elevation data, particularly for the Fort Craig model, when available;
- update of river packages using updated FLO-2D simulations incorporating higher resolution land surface elevation data, when available;
- refined representation of the falling limb of the flood hydrograph, allowing for more gradual reduction in overbank water and improved simulation of flood-wave recession;
- refinement of drain bed elevations and drain water surface elevations for specific conditions, as additional data become available.

The incorporation of such additional data into the riparian groundwater models will improve their physical representation of the hydrologic system and their utility in evaluating surface water/groundwater interactions of interest to water management and river restoration.

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