Riparian Groundwater Models for the Middle Rio Grande: ESA Collaborative Program FY04

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March 2006

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Prepared for:

The Middle Rio Grande Endangered Species Act Collaborative Program

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EXECUTIVE SUMMARY

Project Goals

This study, conducted under the FY04 Endangered Species Act (ESA) Collaborative Program by S.S. Papadopulos & Associates, Inc. (SSPA) and the New Mexico Interstate Stream Commission (NMISC), expands on work conducted under a first-year project in FY03. This project refines the three riparian groundwater models developed in FY03 for simulation of shallow groundwater conditions and exchanges between surface water and shallow groundwater within the floodplain of the Rio Grande, develops two new riparian models, and develops a framework for extending models south to Fort Craig. The riparian models were developed to support analysis of water management and restoration plans that are impacted by dynamic hydrologic processes occurring in this area.

The riparian models developed under the FY03 project cover the area from Angostura Diversion Dam, north of Albuquerque, south to the Valencia-Socorro county line. The two new riparian models developed under this FY04 project, the Bernardo and Socorro models, cover the area from the Valencia-Socorro county line to about one mile south of the Highway 380 bridge near San Antonio. Model frameworks were developed for two additional models extending modeling coverage south to Fort Craig.

The study area was selected based on the prevalence of current and proposed restoration projects. For these projects to be ultimately successful, understanding the nature of shallow groundwater conditions and associated river seepage loss/gain in response to flow events and physical conditions proposed under restoration is required. The suite of five models now available can be used to evaluate hypothetical conditions and sensitivities relevant to water supply and habitat restoration goals.

The Bernardo and Socorro models are used to test hypotheses concerning the relationship of shallow riparian groundwater conditions and river seepage rates to variations in (a) regional groundwater conditions, (b) spring run-off magnitude and duration, and (c) vegetation type and coverage. Potential future applications for the models may include assessment of the sustainability of hydrologic conditions needed for successful restoration projects under varying water supply conditions; analysis of river system conveyance efficiency under alternate river operational scenarios; and, evaluation of changes in river system depletions associated with modification of the riparian environment. An approach for applying the models to evaluate hydrologic changes associated with a river restoration project is described.

Methods for Riparian Model Development

The models simulate hydrologic conditions in the Rio Grande corridor, riverside bosque, and riverside drains. Hydrologic inflows and outflows in this area include river leakage, riverside drain gain/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 groundwater models were developed in MODFLOW 2000. A very fine mesh (with cell size of 125 x 250 feet) is used for the models to allow for detailed assessment of riparian groundwater conditions and surface water-groundwater exchanges. The riparian models represent three layers within the alluvial zone (upper 80 feet) and a fourth layer in the Upper Santa Fe Group. The models utilize FLO-2D to describe the river condition under various flow magnitudes. The wetted channel, water depth and occurrence of overbank flow are variably represented in sets of model boundary conditions for selected river flow magnitudes of 100, 500, 1,000, 2,000, 3,000, 5,000, 7,000, and 10,000 cubic feet per second. Set within the framework of the regional USGS Groundwater Flow Model of the Albuquerque Basin and the NMISC Regional Groundwater Flow Model for the Socorro Basin, initial model heads, regional groundwater boundary conditions, and layer hydraulic properties are interpolated from the regional groundwater model files.

Further Development of Existing Models (Upper and Lower Albuquerque, Belen)

The Upper Albuquerque, Lower Albuquerque, and Belen models, initiated under FY03 funding, were further developed as part of the FY04 project. Additional development was conducted in three areas:

- Lateral boundary conditions specified in the General Head Boundary package were modified to represent boundary conditions at distal locations. Lateral boundary conductance calculations were modified to incorporate the offset between river centerlines in the riparian and regional models, where the two differ in location as a result of grid cell resolution.
- Evapotranspiration-depth relationships for plant sub-groups were revised to represent both plant evapotranspiration (ET) and evaporation from flooded lands with a single ET curve. These relationships were used to develop a multi-stress period Riparian ET package allowing temporal variation in evapotranspiration. Over the period of the transient model runs, evapotranspiration varies from zero to 0.8 feet per month. This variability is captured in the new transient Riparian ET package.
- Representation of overbank flow was modified to allow overbank water elevations in excess of river stage elevations and to allow partial flooding of riparian model cells by adjusting conductance values.

This work yielded new MODFLOW General Head Boundary, Riparian ET, and River packages for the Upper and Lower Albuquerque and Belen riparian models. These model improvements resulted in small changes to groundwater elevations and seepage rates as simulated with the FY03 model versions.

These developments were similarly applied in creating model files for the Bernardo and Socorro models under this FY04 project. Consequently, all five riparian models are structured similarly.

Preliminary Model Results, FY04 Models (Bernardo and Socorro)

Preliminary simulations were made using the Bernardo and Socorro models developed under this FY04 project to assess the reasonableness of the models. The simulations included steady-state runs at each of the selected river flow levels and transient runs in which a spring run-off period was simulated following several preceding fall and winter months. Where available, observation well data were compared to simulated water levels as a check on model performance. The

comparisons indicated that the models perform within a reasonable range. However, a rigorous calibration was not conducted. Model calibration to local conditions using the most up-to-date data is recommended prior to application of the models to specific restoration questions.

The FY04 riparian models were used to evaluate hypotheses regarding potential conditions within and surrounding the riparian groundwater zone and to illustrate how water levels and river seepage rates are affected under different circumstances, including alternate vegetative, regional water level, and antecedent water supply conditions. These results, while best considered "qualitative" due to the number of assumptions built into the test cases, provide insight into riparian zone sensitivities that may be important to water management and river restoration actions. For this application, the historic base case was used to represent conditions prior to, during, and following a spring run-off pulse. Then, modifications were made to various elements of the base case to test hypotheses regarding the riparian groundwater system and groundwater-surface water interactions through the spring run-off cycle. Results are briefly described below.

- *Alternate riparian vegetation*: It was assumed that riparian vegetation classes with maximum evapotranspiration rates of 4 acre-feet per year were replaced with vegetation classes with maximum evapotranspiration rates of 3 acre-feet per year. Given the assumed distribution of riparian vegetation classes and associated rates for the modeled regions, the simulated groundwater elevation difference ranged from 0 to 2.5 feet, with elevated groundwater under the alternate vegetation assumption. The river seepage loss was reduced by one to two tenths of a cubic foot per second per mile with the alternate vegetation assumption. Impacts were more noticeable in the Socorro model, and for both models, were greatest where vegetation classes with the higher ET rates were concentrated.

- *Alternate regional groundwater conditions*: Model boundaries were adjusted from the base case to represent modified, hypothetical regional groundwater and drain boundary elevations. Under the lower regional condition assumptions, the riparian corridor was significantly "drier" and increased river seepage rates occurred. This would impact the maintenance of target river flows for habitat, particularly in low flow periods; also, greater losses throughout the season would have impacts on water delivery via the river channel. The degree of change was variable by model reach and by season.

- *Alternate antecedent conditions*: Assumptions were made regarding river flows that might typify a low or high supply antecedent period, i.e., a period of several years drought or above-average supply. As simulated in this scenario, the impact of the antecedent condition was evident only immediately following the condition, and was minimal by the beginning of the spring runoff. However, in practice, low antecedent flow conditions will likely result in altered boundary conditions. The degree to which boundary conditions are altered, how persistent the boundary conditions are during and following the spring event, and the magnitude and duration of the spring runoff will work in concert to determine the full impact of antecedent conditions.

Application to Restoration Projects and Water Management

Restoration Project Planning, Design and Operation

The riparian models developed to date, though requiring additional data input to support specific restoration design questions, illustrate sensitivities that may be important in restoration planning. The simulations provide a basis for understanding seasonal changes in seepage rates and shallow groundwater conditions that may be critical to the success of a river or bosque restoration project. The primary insight derived from the simulations is that the riparian environment is a dynamic environment impacted by multiple processes that manifest differently under different conditions. The riparian models can be used in a number of ways to support restoration activities, including:

- *Site selection/assessment*: Simulations can be conducted to assess general characteristics, for example, the likelihood of a reach being relatively "wet" vs. relatively "dry" under a range of conditions. Assessed characteristics may include anticipated ranges of river seepage, an important parameter to understand for the maintenance of river flows that are judged desirable for aquatic species. Similarly, the depth to water below land surface and maintenance of desired shallow groundwater conditions in the riparian zone can be assessed with regard to Southwest Willow Flycatcher habitat.

- *Feasibility studies*: Alternate restoration approaches can be simulated and assessed to identify whether the project is likely to achieve hydrologic objectives under an expected range of potential climate and water supply conditions.

- *Project design*: Sites that have been selected for design and construction can be modeled to assess changes in hydrologic conditions. For example, modified river bed or drain elevations will have a large impact on hydrologic conditions within the riparian zone. Similarly, channel configuration may be important to the maintenance of saturation in particular localized areas, or for the control of river seepage rates. A specific project site can be modeled with a range of design parameters to compare alternatives with respect to hydrologic performance criteria.

- *Project monitoring and operations/maintenance*: Hydrologic data pertaining to a specific project can be monitored following project start-up and used to refine model characteristics for the project vicinity. Then, using the refined model, change under forecasted or potential future conditions can be simulated, possibly providing an opportunity to identify and implement additional project controls to improve project success under changing conditions.

Depending on the nature of a specific application, the riparian models can be used with varying degrees of additional data input or modification. To support site selection and assessment, relatively limited work would be needed. Appropriate levels of model refinement increase through the progression from assessment, feasibility study to design. Through this progression, model applications should be supported with increasing levels of locally relevant data. Useful data would include reach-specific paired river and drain seepage runs and concurrent water-level

monitoring in shallow piezometers within the reach. Drain and river bottom elevations should also be measured to increase the spatial resolution of these data within the area of interest. Regional aquifer boundary conditions, presently adapted from the regional models, should be re-assessed for appropriateness in the context of the proposed restoration and projected regional conditions.

Water Management

Key among water management priorities is the efficient conveyance of water to meet demands, whether the demand is driven by urban, agricultural, environmental or interstate compact needs. The efficient conveyance of water requires knowledge of river and drain seepage losses/gains under alternate supply, regional and routing conditions. While river and drain seepage losses/gains can be quantified through field investigation, it would be impractical and expensive to conduct enough field investigations to characterize the losses/gains under all potential conditions that may be important to water management. The ability to transfer knowledge gained under one set of conditions to another set of conditions can be rapidly assessed using the riparian models, assuming that a sufficient range of measured information is available for model calibration. Improved understanding of riparian system dynamics and relationships through modeling analysis can be applied to the following situations:

- Quantification of increased depletion (identification of water needs) for river or bosque restoration projects;
- Quantification of changes in seepage loss and return flows under altered river or bosque conditions (i.e., what portion of river losses are captured by drains, and how timing and location of returns are modified);
- Assessment of changes in river losses under alternate water conveyance alternatives, for example, if drains are more heavily utilized as conveyance channels for irrigation water;
- Assessment of changes in river losses under different river operation scenarios, i.e., as a function of flow magnitude or timing of delivery.

The collection and incorporation of additional data into the model will improve its predictive value for specific applications.

The riparian groundwater models provide a tool for evaluating water management alternatives that are sensitive to surface water / groundwater interaction in the riparian zone. The application of the models to such questions may identify improvements in conveyance and water delivery efficiency in the river/drain system that would benefit the region in meeting diverse demands with a limited water supply.

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1.0 INTRODUCTION

This report presents the results of development and refinement activities for a series of shallow, riparian-zone groundwater models (riparian models) associated with the Middle Rio Grande in central New Mexico. These models have been 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 Angostura to San Antonio, New Mexico. This work was performed under Fiscal Year 2004 (FY04) 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 (FY03) funding from these entities. FY03 work is described in (SSPA, 2005).

The work performed under this FY04 portion of this project includes:

- refinement of three shallow riparian models developed in the FY03 phase of the project to simulate surface-water/groundwater interaction along the Rio Grande between Angostura (approximately 25 miles north of Albuquerque) and Belen, New Mexico;
- development of two riparian models, representing the reach of the Rio Grande between Belen and San Antonio, New Mexico; and,
- development of two model frameworks to extend model coverage to the vicinity of Fort Craig, New Mexico, which can be considered the upper limit of Elephant Butte Reservoir.

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. The two new riparian models described in this report cover the area from the Valencia-Socorro county line south to about one mile below the Highway 380 bridge near San Antonio, NM. 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, Elizabeth Jones, and Milos Novotny.

This report describes model development and refinement, including input data, assumptions and calculation methods, and the application of the models to assess shallow groundwater conditions and surface-water exchanges under alternate hypothetical conditions.

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 and sustainability of stream restoration projects under varying hydrologic or physical conditions.

The FY04-funded work described in this report extends the riparian model coverage provided by the three existing riparian models southward, from the Valencia-Socorro County line to Elephant Butte Reservoir. This region is an area where the river is subject to drying in late-summer and where water losses to seepage can be significant. It is therefore a critical area of concern for agencies involved in river management to support the needs of the Rio Grande Silvery Minnow. Understanding the nature of shallow groundwater conditions and associated river loss or gain through seepage in response to flow events and physical conditions can greatly enhance the ability to manage the river in a way that maintains continuity in key habitat areas. The habitat conditions (presence of open water or saturated soils) 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 constraints.

1.2 Study Area Description

The study area for this project, including both the FY03 and FY04 phases, extends along the Rio Grande from the Angostura Diversion Dam to the northern edge of Elephant Butte Reservoir, a distance of 130 miles (Figures 1.1 through 1.3). This area lies within the Middle Rio Grande region of New Mexico, defined as the reach of river valley extending from Cochiti Reservoir in the north to Elephant Butte Reservoir in the south. Water use within the Middle Rio Grande is subject to limits set forth under the Rio Grande Compact. The Middle Rio Grande region includes groundwater within the *Quaternary alluvium* and the *Santa Fe Group* aquifer systems of the Albuquerque and Socorro basins.

Groundwater conditions in the Albuquerque and Socorro basins are affected by climate, by irrigation, and by pumping for various uses. Following intensified irrigation in the valley, the shallow groundwater elevation rose and some lands became waterlogged. These lands were subsequently reclaimed with the construction of drains that collected water from waterlogged soils in the valley and lowered shallow groundwater levels. Over the past half century, groundwater pumping has steadily increased for municipal and industrial purposes, along with some agricultural use. The pumping has resulted in significant water level declines in the deep aquifer in the Albuquerque region; however, there is little impact from pumping south of Belen. Groundwater pumping ultimately impacts stream flow in this stream-connected aquifer setting.

The surface water supply in the Middle Rio Grande region is fully appropriated. On average, consumptive use of surface water is distributed among various sectors as follows: 26%, agriculture; 37%, riparian vegetation; 9%, open water evaporation (from the river and Cochiti Reservoir); 25%, evaporation from Elephant Butte Reservoir; and 3%, urban use[1] (S.S. Papadopulos & Associates, Inc., 2004). However, environmental needs have been gaining increased attention in recent years with the listing of the Southwest Willow Flycatcher and the Rio Grande Silvery Minnow under the ESA. As a result, time and effort are increasingly being devoted to establishing and maintaining habitat for these species.

[1] These percentages do not reflect consumption from groundwater. The portion of surface water consumed by urban uses will increase in the future as lagged impacts of past pumping reach the river, and if and when direct diversion from the river for municipal use occurs.

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

1.3 Riparian Models

Under FY03 ESA Collaborative Program funding, a set of three riparian groundwater models were developed for the near-river area along the Rio Grande in three selected sub-reaches (Figure 1.1):

- ***Upper Albuquerque (UAB)*** - from the Angostura Diversion Dam south to below Interstate 40 (I-40);
- ***Lower Albuquerque (LAB)*** - I-40 south to below the Bernalillo-Valencia county line; and,
- ***Belen (BEL)*** - from the Bernalillo-Valencia county line to the Valencia-Socorro county line.

These models were localized, allowing for a focused study of the transient riparian conditions. All three models utilized FLO-2D to describe the river condition under various flow regimes, regional conditions, and channel conditions. Set within the framework of the regional Albuquerque Basin model, initial model heads and layer hydraulic properties were interpolated from the Albuquerque Basin groundwater model files.

This study builds upon these three models, further developing the existing models and constructing two additional models to extend modeled coverage south to the Highway 380 Bridge in San Antonio, NM, which is approximately five miles north of the Bosque del Apache National Wildlife Refuge. The two models constructed in this study are (Figure 1.2):

- ***Bernardo (BDO)*** – from the Valencia-Socorro county line south to San Acacia Diversion Dam; and

- ***Socorro (SOC)*** – from the San Acacia Diversion Dam south to about one mile below the Highway 380 bridge.

Model frameworks are provided for two additional sub-reaches, which could be used to extend model coverage to the northern end of Elephant Butte reservoir (Figure 1.3):

- ***Bosque del Apache (BDA)*** - from about 1.3 miles north of the Highway 380 bridge south to about 1.5 miles south of where the Rio Grande exits the Bosque del Apache ; and

- ***Fort Craig (FTC)*** – from about 1.5 miles north of where the Rio Grande exits the Bosque del Apache to the vicinity of Fort Craig, which can be considered the northern edge of Elephant Butte Reservoir

These frameworks, though not fully parameterized, include crop and riparian coverages, land surface elevations, and boundary conditions. They presently serve as a repository for data relevant to modeling.

1.4 Report Organization

The main body of this report describes further development of the existing three shallow riparian zone models, development of two shallow riparian zone models, and construction of model frameworks for two additional riparian models that could be used to extend coverage to the north end of Elephant Butte Reservoir.

Section 2 describes the resources available for model development. Section 3 describes the riparian model design. Section 4 describes refinements to the Albuquerque and Belen (FY03) models. Sections 5 and 6 relate to the development of the Bernardo and Socorro models in the FY04 phase of this project. Section 5 describes historic groundwater conditions within the new study area. Section 6 describes preliminary model simulations and hypothesis testing, where hypotheses were structured to evaluate sensitivities important to water supply and habitat restoration goals.

Section 7 outlines a general approach to modifying the models for application to restoration projects. Section 8 discusses implications of study results for restoration and water management activities, approaches for model application, and general recommendations for data collection to support model refinement. To maintain readability of the report, detailed technical

material and supporting data are organized within several appendices. These appendices include summaries of key data sets and metadata.

2.0 RESOURCES AVAILABLE FOR DEVELOPMENT OF RIPARIAN MODEL

Data to support the riparian model development have been compiled in the following areas:

- Existing regional groundwater models results
- Groundwater elevations from shallow monitoring wells;
- Drain and Low-Flow Conveyance Channel (LFCC) bed and water-surface elevations;
- Riverbed elevation (from the U.S. Bureau of Reclamation (USBR) Aggradation/Degradation lines);
- Gaged river flows;
- Riparian vegetation classification and water use characteristics; and,
- Measurement-derived river seepage estimates.

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 6.

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:

- United States Geological Service (USGS) Groundwater Flow Model of the Albuquerque Basin (Kernodle et al., 1987; Tiedeman et al., 1998; McAda and Barroll, 2002): Through the past decade, the USGS has developed several versions of a regional groundwater model for the Albuquerque Basin (Albuquerque Basin model), with the McAda and Barroll (2002) model representing the most recent version. The Albuquerque Basin model characterizes groundwater conditions within the valley alluvium and the basin fill from Cochiti Reservoir in the north to San Acacia in the south. With a regional

focus, the Albuquerque Basin model does not offer the resolution to evaluate conditions within the river floodplain, i.e., how alternative river management options would impact localized groundwater losses or gains, ponding, and the depth of saturated conditions in the near-river zone. The Albuquerque Basin model is used in this study to define boundary conditions on the northern four 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. Additionally, this model provided initial estimates to the riparian models for several hydrogeologic parameters.

- 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 Socorro riparian groundwater model, 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: This model represents the operations of reservoirs and provides a routing analysis to simulate river hydrographs under a variety of management scenarios. Impacts of regional groundwater pumping and river losses/gains due to multiple factors are represented using empirical relationships or assumptions. These specifications attempt to capture the “present” condition and are static with respect to water use and groundwater conditions. URGWOM is not sensitive to the modification of groundwater – surface water interactions due to changes in any of these factors in the present. Though these factors may not be important with respect to flood routing, or general river operational analyses, they can be important to how the floodplain responds to a flood event or recession, and are often important in determining localized river loss/gains. 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 (Tetra Tech, 2004): 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 between the river and riverside drains. Several sets of wells have been installed within the riparian zone in recent years. These have been installed by two primary entities, for various purposes. These well groups, and the associated period of record, include:

- UNM Bosque ET towers and wells, 1999 - 2004;
- NMISC / ACOE piezometers and staff gages, 2003-2004.

The data obtained from these sources are described below.

2.2.1 UNM Bosque ET Monitoring Sites

The University of New Mexico (UNM) maintains several evapotranspiration and groundwater monitoring sites throughout the Middle Rio Grande Valley. Groundwater monitoring sites are located within the Bosque in the South Valley of Albuquerque, Los Lunas, Belen, Bernardo, the Sevilleta National Wildlife Refuge (NWR), and the Bosque del Apache NWR. At each of these locations, groundwater levels are monitored in up to five wells. Wells are arranged with a central well surrounded by four satellite wells located approximately 40 meters distance in each of the cardinal directions. Each monitored wells is instrumented with a pressure transducer recording water elevation data every 30 minutes. Table 2.1 lists data available at the Bernardo and Sevilleta NWR sites; well locations relative to the Bernardo model boundaries are shown on Figure 2.1. Hydrographs for the Bernardo and Sevilleta wells are provided in Appendix B (figures B.1 and B.2)[2].

[2] Bernardo water levels, though provided as elevations relative to mean sea level, should be considered relative only. Available ground surface elevation data are either taken by hand-held GPS or are survey grade but referenced to unknown and varying datums. Data shown in Figure B.1 are referenced to hand-held GPS elevations.

2.2.2 NMISC / ACOE Piezometer Data

Well transects across the riparian zone were drilled (SSPA, 2003) at several locations in the Socorro Basin 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. These transects have been monitored by the NMISC, with assistance from NM Tech and SSPA, for a period of several years. Groundwater levels from four monitoring well transects located within the Socorro model development area between San Acacia and the north boundary of Bosque del Apache were used in this study. In addition to the well network, staff gages are located at each transect in the Rio Grande and adjacent canals and drains to monitor surface-water levels at the transect locations. Table 2.1 lists data available at each of the monitoring wells; Table 2.2 lists data available at each of the staff gages. Well locations relative to the Socorro model boundaries are shown on Figure 2.2, and staff gage locations are shown in Figure 2.3. Geologic materials at the observation wells are shown in Figures 2.4A and B. Hydrographs for the monitoring wells are provided in Appendix B, figures B.3 through B.6.

- The first transect San Acacia (designated "SAC") is located 1 mile south of the San Acacia Diversion structure.
- The second transect, Escondida (designated "ESC"), is located in an area with an extensive riparian corridor and significant river losses.
- The third transect, Brown Arroyo (designated "BRN"), is located at the confluence of Brown Arroyo and the Rio Grande. At this location, there is agricultural land, which is primarily used for grazing, on the west side of the river, and broad, low-lying expanses of riparian forest, with shallow groundwater, on the east side.
- The fourth transect is Highway 380 (designated "HWY"), is also in a location with agricultural land only 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).

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. 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 60 feet below land surface; "C" wells have 5-foot screens in the lowermost portion of the river alluvium, typically, located between 75 and 90 feet below land surface.

2.3 Drain and Low-Flow Conveyance Channel Bed Elevation Data

To characterize bed and water-surface elevations in the riverside drains within the riparian models, data were compiled from two sources: a topographic survey completed in 2001 for the NMISC seepage analysis (SSPA, 2001); and a survey completed in 2004 by SSPA/MEI (SSPA and NMISC, 2005, Appendix D).

Drain bed elevations for the FY03 models are described in (SSPA and NMISC, 2005). In development of the Bernardo model, two drain-bed survey points from the 2004 dataset, measured on either side of Bernardo Bridge, were used in the interpolation of drain bed elevations. Drain bed elevations were calculated from the 2001 dataset (Table 2.3) by subtracting the maximum depth of water from the surveyed water surface elevation. In the 2001 dataset, multiple records of drain bed and water surface elevation were available for a single location because surveys were completed for multiple days. The minimum water surface elevation measured at each location was used in model development, on the assumption that it most likely represented periods without tailwater or other operational water contribution. The minimum drain bed elevation and minimum water surface elevation at each location were used for interpolation of drain-bed elevations within the Bernardo model area, as described below.

Within the Bernardo grid, drains were grouped based on availability of data, reach, and side of river. Linear interpolation was used to calculate drain bed elevation between survey points along the drain groups. Where extrapolation was necessary (for example, from the last location on a drain to the top or bottom end of the drain), the average slope for that drain group was used. The Lower San Juan Riverside Drain, on the east side of the Bernardo model, is broken by the Arroyo Los Alamos, approximately halfway down the model. At this location, drain water is diverted back to the river. For the Lower San Juan Riverside Drain below this arroyo, no drain data are available. Accordingly, just below the arroyo the drain thalweg was set at 2.5 feet below the drain thalweg elevation at the closest survey point upstream of the arroyo. The drain outlet to the Rio Grande was set equal to the Rio Grande river bottom at the drain-river confluence.

For the Socorro model, LFCC bed and water surface elevations were extracted from the 1992 USBR Aggradation/Degradation lines (Ag/Deg lines; discussed further in Section 3.3). A

linear interpolation was applied to calculate elevations at the mid-point of each of the intersected model grid cells. LFCC water depth was interpolated from field measurements at the San Acacia, Escondida, Brown Arroyo and Highway-380 sites. Depths were extrapolated to the northern and southern ends of the active model by extending the interpolation equation, using the slopes in the adjacent reaches.

2.4 Riverbed (Thalweg) Elevation

River thalweg elevations were obtained from the 1992 USBR Aggradation/Degradation lines (Ag/Deg lines). The Ag/Deg lines are based on 1992 aerial photography, photo-interpreted by the USBR. Ag/Deg line bed elevations were estimated from the average flow depths at the time of the photography (estimated flow depths at the time of the photography were subtracted from the water-surface elevation to produce an estimated average bed elevation). These average depths/elevations assumed a flat river bottom for all areas inundated at the time of the photography. The minimum river elevation (i.e. the average depth assigned to all inundated areas) for each Ag/Deg line was extracted from the dataset for use as river thalweg elevation within the riparian models. A linear interpolation was applied to calculate values at the mid-point of each of the intersected riparian model grid cells.

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 (the mean difference between the two datasets is less that 0.4 feet). FLO-2D elevations are given in NAVD88 (Tetra Tech, 2004); therefore, it is inferred that 1992 USBR Ag/Deg elevations are referenced to NAVD88.

2.5 Riparian Vegetation Classification

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

- Vegetation mapping coverages performed 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.

2.6 Riparian Evapotranspiration Rates

Extensive research into 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, weather conditions, and season. ET rates for salt cedar, cottonwood, and mixed bosque used in the ET Toolbox (USBR, 2003) and published by researchers are shown in Table 2.4. As shown, there is significant variation in measured ET rates along the Middle Rio Grande corridor. Figures 2.5A and B illustrates 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 2003 (provisional data, Biology Department, University of New Mexico, James Cleverly). 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. For example, a dense cottonwood site subject to regular spring flooding in Albuquerque area can consume more than 4 feet per year while a rarely flooded dense salt cedar site at Bosque del Apache can use between 3 to 4 feet per year.

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.

2.7 River Seepage Estimates

Field measurement programs to estimate seepage from the Rio Grande were undertaken by the NMISC in the late summer of 2000 through early winter of 2001 in the San Acacia reach of the Rio Grande and in the summer of 2001 in the Belen reach (SSPA, 2001 and 2002b). Tables 2.5A through 2.5C summarize the measurement results. The field measurements, and abstractions from their results, are described below.

2.7.1 Bernardo Reach

Seepage runs were conducted on the Rio Grande during June and July of 2001 for various sub-reaches within the Bernardo model. Measurement stations included Blue Cup, the Lower Sabinal Drain, upstream of highway US 60, downstream of Drain Unit 7, upstream of San Acacia #3 and upstream of San Acacia #2 (shown on Figure 2.7). Flow conditions at the top of reach are noted in Table 2.5a. River losses ranged from about 1 to 8 cfs per mile, varying with river section and river flow; and two sub-reaches exhibited gains during one of two or three measurement events[3]. In general, seepage rates are estimated at 5 cfs per mile, or less, and suggest that this section of river is a losing reach during summer months.

Seepage runs were conducted during July of 2001 on two drains within the Bernardo reach: the San Juan Riverside Drain and Drain Unit 7. Measurement stations are shown on Table 2.5b. At this time, measurements indicated that both the San Juan Riverside Drain and the upper section of Drain Unit 7 were losing small quantities of flow (1-2 cfs/mile). Groundwater

[3] Regarding the apparent gains, questions regarding the possibility of inflows not found during scouting were raised but not confirmed.

elevations during these events may have been suppressed due to high riparian groundwater use during June and July; in addition, in this reach drain bottoms generally lie above the river bottom and the drains tend to function as conveyance channels. On the other hand, the lower section of Drain Unit 7 exhibited gains estimated at 4.8 cfs per mile during the July measurement event. Additional seepage runs would be useful to confirm and to better understand seepage conditions in the Bernardo region.

2.7.2 Socorro Reach

Between August 2000 and February 2001, several seepage runs were conducted (SSPA, 2001) on various sub-reaches of the Rio Grande and Low Flow Conveyance Channel between San Acacia and Elephant Butte Reservoir. Data for three Rio Grande sub-reaches of interest are presented in Table 2.5b: San Acacia to Escondida, Escondida to Highway 380, and Highway 380 to the north boundary of Bosque del Apache. The flow in the Rio Grande at San Acacia at the time of each seepage run is also shown.

The seepage runs suggest that the river experiences on average losses of approximately 5 to 7 cfs per mile; all three sub-reaches were predominantly losing reaches. Losses were found to be greatest in the reach between Escondida and Highway 380, averaging 9 cfs per mile for these four summer and one winter seepage runs. Losses were smallest in the San Acacia to Escondida sub-reach, averaging 2 cfs per mile. The sub-reach between Highway 380 and the north boundary of the Bosque del Apache showed variability with an average of 8 cfs per mile during three summer seepage runs and a slight gain in the winter run, however, the shorter length of this sub-reach increases the uncertainty in the seepage estimate.

Low Flow Conveyance Channel seepage estimates are shown on Table 2.5c; average gains range between 4 and 7 cfs per mile. The greatest gains between San Acacia and the north boundary of the Bosque del Apache were found between the 1200 Structure in Socorro and Brown Arroyo, where calculated gains averaged 11.6 cfs per mile. The magnitude of gains is related to the groundwater level with respect to drain elevation; and, irrigation season activities have impacts on the groundwater level.

3.0 RIPARIAN MODEL DEVELOPMENT

Five groundwater models and two model frameworks have been developed to cover the Rio Grande and riparian corridor between the riverside drains, extending from the Angostura Diversion Dam in the north to Fort Craig in the south, which can be considered the northern end of Elephant Butte Reservoir. The spatial extent of each model is described in Section 1.3. This approach, involving separate models, reduces model grid size and associated model run time, and provides a suite of small, localized models that can be run quickly and efficiently to answer localized questions.

The riparian groundwater models were developed in MODFLOW 2000 (Harbaugh et al., 2000). The groundwater models utilize output from the Middle Rio Grande FLO-2D Flood Routing Model (Tetra Tech, 2004) 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 riparian models to allow for detailed assessment of riparian groundwater conditions and surface water-groundwater exchanges.

The riparian models represent 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 of exchanges with the deeper aquifer.

3.1 Model Grid

The northern four riparian models employ grids with identical cell sizes and rotations. Cells are 125 feet wide by 250 feet long, oriented lengthwise along the river. The model grids are rotated 15.44 degrees clockwise of north, so that, on average, their long-axis parallels the Rio Grande. The models are configured as follows:

- Upper Albuquerque model – 255 cells wide by 458 cells long;
- Lower Albuquerque model – 194 cells wide by 312 cells long;
- Belen model – 168 cells wide by 551 cells long;
- Bernardo model – 128 cells wide by 453 cells long.

Adjacent models overlap by roughly one mile.

The Socorro model employs a grid with horizontal cell dimensions as noted above, but different horizontal orientation. The Socorro grid is aligned north-south, reflecting the more north-south orientation of the Rio Grande below San Acacia Diversion Dam. The Socorro model is configured as follows:

- Socorro model – 168 cells wide by 524 cells long.

The Bernardo and Socorro models do not overlap. The San Acacia Diversion Dam sits on the boundary between the Albuquerque and Socorro groundwater basins. Though joined by the Rio Grande, the groundwater systems of these two basins are relatively distinct, and boundary conditions can be set for each model at the dam.

The Bosque del Apache and Fort Craig frameworks employ grids of 125 by 250 foot cells rotated 25 degrees clockwise of north, again allowing the long-axis of the cells to parallel the Rio Grande. The frameworks are configured as follows:

- Bosque del Apache framework – 192 cells wide by 356 cells long;
- Fort Craig framework – 194 cells wide by 266 cells long.

The Bosque del Apache framework overlaps the Socorro model by about three miles; similarly, the Fort Craig and Bosque del Apache frameworks overlap by about three miles. 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 limited observation data.

3.2 Model Layers

Each model is discretized in the vertical direction into four layers. The top three layers represent the Rio Grande alluvium and the fourth layer represents the top of the Santa Fe Formation. Model layers thickness 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.

The model layers in the northern four riparian groundwater models are related to the layers defined in the 2002 Albuquerque Basin Groundwater model. Model layer 1 generally corresponds to the Albuquerque Basin model layer 1 (beneath the river, the thickness of

Albuquerque Basin model layer 1 is 30 feet). Model layers 2 and 3 generally correspond to the Albuquerque Basin model layer 2 (beneath the river, the thickness of Albuquerque Basin model layer 2 is 50 feet). The fourth layer corresponds to Albuquerque Basin model layer 3, and like Albuquerque Basin model layer 3, is 100 feet thick throughout.

For the Socorro model and Bosque del Apache and Fort Craig frameworks, examination of well logs and test data suggested that the vertical discretization used in the northern four models also was suitable for the Rio Grande valley within the Socorro Basin; accordingly, layer thicknesses were set equal to those used in the northern models. For the Socorro model and the two model frameworks, 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.

Land surface elevations (for the top of layer 1) for the Upper Albuquerque, Lower Albuquerque and Belen models were extracted from a 10-meter, re-sampled Digital Elevation Model (DEM) from 1-foot Digital Terrain Model (DTM) data used for developing FLO-2D model. Data gaps in the re-sampled DEM, primarily within the Upper Albuquerque sub-model, were filled using USGS 10-meter DEMs. The USGS 10-meter DEMs were used solely as a secondary source to supplement grid cells that did not have data from the primary DEM. A +4.44 foot vertical shift was applied to the USGS data to smooth apparent differences between the two sources.

For the Bernardo and Socorro models, land surface elevations were averaged from the original Digital Terrain Model (DTM) data used for developing FLO-2D model. For the Bernardo sub-model area, DTM data were relatively regularly spaced and covered the entire active model grid; data were averaged up to grid resolution to provide surface elevations for the active model grid. For the Socorro model area, the DTM data were irregularly spaced; accordingly, the data were used to create a surface that was re-sampled at a regular 15-meter interval. The re-sampled data were then averaged up to grid resolution to provide surface elevations for the model. As for the northern three models, data gaps in the Bernardo and Socorro re-sampled DTM were filled using USGS 10-meter DEMs. The USGS 10-meter DEMs were used solely as a secondary source to supplement grid cells that did not have data from the

primary DEM. For the Bosque del Apache and Fort Craig frameworks, land surface elevations were averaged to grid resolution from USGS 10-meter DEM data.

3.3 Boundary Conditions

The active model cells were designated to include the Rio Grande corridor and bordering riparian bosque, bounded by the riverside drains and Low-Flow Conveyance Channel (LFCC). This resulted in long, thin active model areas. The shallow groundwater system in this zone is typically recharged by river seepage. Boundary conditions providing significant control on the shallow riparian groundwater elevations include regional (lateral and deeper) groundwater elevations and riverside drain and conveyance channel stage. Three MODFLOW packages were used to specify boundary conditions within the model. The River Package (RIV, or, river package) was used to address the three types of surface water conditions within the model: in-channel Rio Grande stage; overbank Rio Grande water elevation; and, riverside drain or LFCC stage. The Riparian Package (RIP, 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 2, 3, and 4 were addressed using the General Head Boundary Package (GHB, or, general head boundary package); this package was also used to set lateral boundaries in model layer 1 in areas lacking riverside drains and the vertical boundary in layer 4. The handling of each of these boundary types is described below.

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. For the hypothesis testing planned under this study, 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. In addition, the RIV files incorporate information relative to the riverside drains (described in Section 3.3.2).

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 3.1A and B, which illustrate daily flow and the step-function used to simulate the sequence of flow conditions preceding and during the run-off seasons in 2001 at Bernardo (within the Bernardo model) and in 2004 at San Acacia (within the Socorro model).

Unlike the step function hydrographs used in the Upper Albuquerque, Lower Albuquerque and Belen models (SSPA and NMISC, 2005) the Bernardo and Socorro step-function hydrographs do not directly follow the gaged Bernardo and San Acacia Rio Grande hydrographs. For both models, the step-function hydrographs were adjusted to correct for FLO-2D losses. For each library flow, the simulated FLO-2D flow at Albuquerque, at the top of the Bernardo model, and at San Acacia Dam (the top of the Socorro model) are shown in Table 3.1. As can be seen, the FLO-2D simulation generates significant losses by the time a given flow reaches the Bernardo or Socorro model. To simulate the gaged flows at Bernardo and Socorro, therefore, the cutoff values used for assigning library flows to gaged flows in the development of the step-function hydrographs were altered to reflect the higher FLO-2D flows required to deliver the expected water to the model.

3.3.1.2 River Channel Representation in River Package

Model cells within the groundwater model grids that fall within the delineated river channel are marked as "in-channel cells" if 50% or more of the cell area falls within the channel extent. The river channel is delineated based on visual identification of active channel areas (i.e., active sediment deposition) interpreted from aerial photos (USBR Aug 2002 color-infrared where available; USBR 2001 black-and-white aerial photography for remainder of area). For each in-channel cell, river bottom elevation, water surface elevation, and conductance are specified.

The river bottom elevation (designated RBOT in RIV Package) is based on interpolation between 1992 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, 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, that lists the channel flow hydraulics including elevation, flow depth, velocity, and discharge by FLO-2D grid

element. A procedure, illustrated in Figure 3.2, was developed and applied to map water surface elevation computed for FLO-2D channel cells to the groundwater model river channel cells[4]. This procedure results in the assignment of a water surface elevation to every identified cell within the channel banks. However, because flow does not necessarily occur over the entire channel width (bank to bank), a correction factor is needed to control the seepage through the river bottom to that which would occur given the actual width of the wetted area. This correction factor is taken as the ratio between the FLO-2D computed channel width for the given flow magnitude and the FLO-2D maximum channel width (*Top Width / Max Top Width*). This correction factor is implemented within the definition of the river conductance (discussed 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).

[4] For the FLO-2D model, in part due to the coarser model grid, channel cells do not always overlie the entire river channel, instead lying to one side or the other of the river. Consequently, a mapping procedure was needed to associate FLO-2D channel cells with their corresponding riparian model in-channel cells. Accordingly, the riparian model grid was dissolved along rows to create row polygons, row polygons were intersected with the FLO-2D channel cells, and FLO-2D channel cell values were assigned to all Riparian model channel cells falling within the intersected row polygon. For Riparian model row polygons intersecting two FLO-2D channel cells, the row polygon was associated with the FLO-2D channel cell with the highest percentage coverage of that row polygon. This is illustrated in Figure 3.2

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 5,000 cfs and greater flows. For the 5,000, 7,000 and 10,000 cfs flows, overbank water surface elevation was calculated as follows:

- Overbank water surface elevations were calculated from the FLO-2D model output by adding water depth from the FLO-2D output file DEPTH.OUT to floodplain land surface elevation from the FLO-2D input file FPLAIN.DAT for each over-bank element, except where the depiction of the river in FLO-2D was two cells wide.

- Where the river in the FLO-2D model is two cells wide, FLO-2D assigns one cell as the in-channel cell (i.e., that cell is included in the FLO-2D output file describing the river channel, HYCHAN.OUT) and associates it with a river bottom elevation. The second in-channel cell is given a land surface elevation from the FLO-2D input file describing the topography of the floodplain, FPLAIN.DAT. However, FLO-2D assigns water depths equal to river stage to both cells. As a result, when the FLO-2D data are used to calculate water elevations, river stage is added to floodplain surface elevation in the second in-channel cell, rather than adding river stage to river bottom elevation. This was corrected by substituting the FLO-2D river bottom elevation for the FLO-2D land surface elevation for all secondary in-channel cells prior to calculating overbank water surface elevations.

- FLO-2D over-bank water-surface elevations were superimposed on the riparian model grid and the total percentage coverage of each riparian model cell by flooded FLO-2D cells was calculated. This percentage was then used to calculate a weighted-average water-surface elevation for the flooded portion of each riparian cell.

- Riparian model overbank water depth was calculated as the difference between the weighted-average water-surface elevation and the riparian model land surface elevation.

- Where the riparian model weighted-average overbank water-surface elevation was less than the riparian model land -surface elevation, water depth was set to null.

- 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 of flooded area within the given cell (equals length of cell, 250 ft);
W is width of flooded area within the given cell (equals 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 Riverside Drains and Low-Flow Conveyance Channel

Water elevations in the riverside drains and LFCC determine the model layer 1 eastern and western boundaries. Drain and LFCC bed elevations were obtained as described in Section 2.3 and in (SSPA and NMISC, 2005). For the Bernardo and Socorro model RIV Packages, initial stage was based on water elevations within the drains at the time of the SSPA seepage study (2001; see Section 2.3 for further detail), and RBOT values were based on interpolated drain bed elevations. For the Upper Albuquerque, Lower Albuquerque, and Belen models, drain elevations are described in (SSPA and NMISC, 2005). Riverside drain and LFCC bed 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 on the riparian models 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 2 through 4 and along the layer 1 perimeter cells where riverside drains are absent. 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 northern four models, to represent the specified head beyond the model boundaries, simulated groundwater elevations were extracted from the 2002 Albuquerque Basin groundwater model (weighted average heads from 1999 non-irrigation and 2000 irrigation seasons were used). Albuquerque Basin model layer 1 groundwater elevations were assigned to riparian model layer 1 GHB cells to represent lateral flow where drains are absent. Albuquerque Basin model layer 2 elevations were used for riparian model layers 2 and 3 GHB cells to represent flow across the lateral boundaries in those layers, and Albuquerque Basin model layer 3 elevations were used to represent flow across the lateral boundaries in the riparian model layer 4. Albuquerque Basin model layer 4 elevations were used in all remaining active riparian groundwater model layer 4 cells to represent vertical interaction with the underlying Santa Fe Formation.

Regional model heads were interpolated to the scale of the riparian model grid cells. 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 D for distance used in each model). Riparian model GHB cell conductances were computed using the distance between the centroid of the riparian model GHB cell and location of the selected interpolated regional model head selected as boundary condition, corrected for the distance between USGS river centerline and Riparian model river centerline. The specifics of these calculations for the Upper Albuquerque, Lower Albuquerque, Belen and Bernardo models are given in the GHB metadata presented in Appendix D.

At its southern end, the Bernardo model extends beyond the southern end of the Albuquerque Basin regional model. For the 27 rows of the Bernardo model affected, heads from the regional model were extrapolated southward to provide boundary conditions extending to the San Acacia Dam. However, it should be noted that these heads are estimates; no control is available to assess their accuracy.

For the Socorro model, simulated groundwater elevations were extracted from the Socorro regional groundwater model for use as GHB heads. 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. As for the northern four models, regional model heads were selected at a distance from the riparian model boundaries where possible. See Appendix D for further detail.

Hydraulic conductance values used in the GHB cells are based on the aquifer properties discussed in Section 3.4, cross-sectional area perpendicular to the direction of flow and a distance factor (Appendix D).

3.4 Initial Hydraulic Properties

3.4.1 Layer Type Specification

All model layers are assigned a layer-type flag of zero, meaning that there is no modification of a cell's saturated thickness as head varies, and no provision for storage conversion. While this layer-type 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. This approximation is typically 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. 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.

A potential drawback for utilizing this simplification is that transmissivity will be fixed in a simulation, rather than adjusting as water levels rise or fall. In the case of this model, changes in the uppermost layer water levels during simulation range over several feet, but are typically less than 10% of the initial layer saturated thickness. Additionally, sensitivity runs have shown that for these models, the utilization of a fixed transmissivity has no significant impact on the results.

With respect to the specification of storage properties, when using the layer-type flag of 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

For the northern four models, initial values for riparian model hydraulic parameters (vertical and horizontal hydraulic conductivity, specific storage, and specific yield) were assigned based primarily on the 2002 Albuquerque Basin model (McAda and Barroll, 2002). A constant hydraulic conductivity of 45 feet per day was assigned throughout layers 1, 2 and 3; a constant hydraulic conductivity of 8 feet per day was assigned to layer 4.

For the Socorro model, horizontal hydraulic conductivity in layers 1 through 3 was assigned based on inspection of well logs and aquifer test data (SSPA, 2003; SSPA, 2004b). 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.

3.4.3 Vertical Hydraulic Conductivity

Vertical hydraulic conductivity is modeled as a fixed percentage of horizontal hydraulic conductivity in this model phase. For the northern four models, the assumed ratio of horizontal to vertical hydraulic conductivity is 10:1 in layers 1 – 3. The ratio of horizontal to vertical hydraulic conductivity in layer 4, and used in the conductance terms of layer 4 GHB cells

representing interaction with the Santa Fe Formation, is 150:1. For the Socorro model, 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 (used in the conductance terms of layer 4 GHB cells). The increased ratio in layer 4 represents the lower 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*:

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

3.4.4 Storage Properties

Specific yield in the uppermost (water-table) layer of the valley alluvium is set in the models at 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 as unconfined, specific storage is calculated as the value of specific yield, 0.2, divided by the layer thickness.

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 x 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 Riparian Evapotranspiration

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. For the 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 8 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
- Open Land
- Open Water

Although the group Open Water is included, the ET rate is currently set to zero since the FLO-2D model simulation accounts for evaporation from the river and overbank water surfaces.

The Open Water 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 8 core groups are listed in Table 3.2. 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 80% coverage by URGWOPS vegetation classification data, IKONOS data were used to designate vegetation coverage. For use in the riparian model development, the IKONOS color-infrared satellite data was transformed to point features and the pixel-values were grouped into the same 8 core groups used for the URGWOPS coverage (Table 3.2). In some areas, sections of cells contained neither URGWOPS nor IKONOS data; in these instances, the cells were designated as containing Unknown Vegetation. For the Bernardo and Socorro models and the Bosque del Apache and Fort Craig frameworks, percentage vegetation coverage by category is listed in Table 3.3. Coverage for the northern three models is described in (SSPA and NMISC, 2005).

3.5.2 Development of ET Rate Curves for use in MODFLOW RIP Package

For each of the seven specified vegetation categories with non-zero ET rates, a riparian ET rate curve was developed based on best available information. The ET rate curves were used in the RIP Package (Maddock and Baird, 2004) to simulate riparian ET as a function of water table depth.

For this phase of model development, a maximum annual ET rate of 3 feet per year is assumed for native cottonwood and 4 feet per year is assumed for salt cedar. The actual ET rate is based on many factors and may vary from the assumed rates. Data show that under some circumstances, cottonwood may use more water than salt cedar (see Section 2.6). 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 seven vegetation categories is listed in Table 3.4. ET curves used in the model are shown in Figure 3.3; six unique curves were developed to represent the vegetation classes represented in the model. The Cottonwood Mixed curve was assigned for Unknown Vegetation, in recognition that most of the unknown vegetation areas lie just outside the riverside

drains in areas that are likely to be disturbed and therefore subject to non-native encroachment. The curves should be reassessed prior to any application of the models for specific sites.

To address cases where the water table rises up to or above the land surface, resulting in open water surfaces, maximum plant ET rates were continued to the land surface and above. 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. For the bare land category, which previously was assigned a maximum ET rate of 1 foot per year, the revised ET rate curve 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. With open water evaporation from flooded lands effectively incorporated into individual plant sub-group ET rate curves, no flooded land category was included in the RIP package. This assures that evapotranspiration is not double-counted for flooded cells.

Continuing the maximum plant ET rate to land surface and above, resulting in the plant ET rate being applied to an open water surface, is a reasonable estimate of flooded land ET. 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.

3.5.3 Development of temporally varying MODFLOW RIP Package

Riparian evapotranspiration 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 create a temporally varying simulation of evapotranspiration using the RIP package, the percentage plant coverage within each cell by each plant sub-group was varied as a function of time within the growing season. 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

3.4. The hypothetical curve was then used to calculate an evapotranspiration weighting factor for each model stress period within a given transient run, and the weighting factor used to scale percentage plant sub-group coverage for each sub-group within each active model cell for that stress period. The same weighting factors were used for each of the vegetation categories. Weighting factors ranged from 0 to 2.4, reflecting the winter periods (October to April) with no transpiration and minimal evaporation, 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.

4.0 REFINEMENTS TO EXISTING RIPARIAN MODELS

In the FY03 Riparian model report, three key aspects of the Upper Albuquerque, Lower Albuquerque and Belen models were identified for further model refinement:

- Lateral boundary conditions specified in the General Head Boundary (GHB) package;
- Representation of flooded land and temporal variability of evapotranspiration (ET) within the Riparian Evapotranspiration (RIP) package;
- Representation of overbank flow in the River (RIV) package.

This section describes the refinements made in these three model parameters for the Upper Albuquerque, Lower Albuquerque and Belen models.

4.1 Lateral Boundary Water Elevations

Several areas in the models were identified where GHB water elevations required correction to improve the representation of the groundwater elevation boundary condition. In these areas, riparian model and regional model river locations differed as a result of differences in grid cell size between these two models, resulting in regional model in-channel or near-river heads having been assigned to riparian model boundary cells. New GHB files were developed for the riparian model using regional model head values for regional model cells located beyond the riparian model boundaries as described in Section 3.3.3.

In the FY03 Upper Albuquerque model, the handling of the GHB water elevations resulted in anomalously high groundwater conditions in the northern portion of the model grid. This was addressed by lowering the Upper Albuquerque GHB elevations by 5 feet at the north end of the model, leaving elevations unchanged at the south end of the model, and lowering intermediate heads via linear interpolation between the two end adjustments. Similarly, in the FY03 Belen model, GHB heads were lowered by two feet throughout the model. Following re-specification of the GHB heads for the Upper Albuquerque, Lower Albuquerque and Belen models as part of the FY04 work, selected heads and associated conductances were used directly. No further adjustments were necessary.

4.2 Riparian Evapotranspiration

Two key changes to the handing of riparian evapotranspiration were made in the models. First, the curves describing the variation in evapotranspiration rate with depth were refined for all plant groups to integrate evapotranspiration when water levels exceed land surface elevation, as described in Section 3.5.2. Second, a temporally varying evapotranspiration package was developed to capture variation in evapotranspiration with season, as described in Section 3.5.3.

4.3 Overbank Flooding

Three changes to the handling of overbank flooding were made. First, water elevations in excess of river elevation were maintained from the FLO-2D output (in the FY03 versions of these models, water elevations in excess of river elevation were set equal to the river elevation); second, partial flooding of cells was allowed and the overbank cell conductance scaled by percentage coverage; and third, secondary FLO-2D in-channel cells were maintained in the overbank flow footprint, but were handled separately to prevent in-channel water elevations from being applied to the land surface. These are described in detail in Section 3.3.1.3.

4.4 Impact of Model Revisions

The revisions described in this section were made to the RIP, RIV and GHB packages of the Upper Albuquerque, Lower Albuquerque, and Belen models, and the Base Case hypothesis testing models were run. The hydrograph used in the Base Case models is shown in Table 4.1. Seepage results from the FY03 versions of these riparian models are shown in Table 4.2, and results from the revised models are shown in Table 4.3. Overall, seepage rate differences between the FY03 and FY04 versions of the models were 1 cubic foot per second (cfs) or smaller for all river, drain and overbank sub-reaches; most changes were 0.3 cfs or smaller. Seepage rate differences were smallest in the Upper Albuquerque model and largest in the Isleta to Tome reach of the Belen model; differences were generally larger at end of winter and decreased over the model run.

Figures 4.1 through 4.3 illustrate the change in head between the FY03 and revised models for Layer 1 of the Upper Albuquerque, Lower Albuquerque and Belen models. Similar to the seepage rate changes, head changed little between the two versions of the models.

5.0 HISTORIC GROUNDWATER ELEVATION CONDITIONS, BELEN TO BOSQUE DEL APACHE

Groundwater elevations in the Middle Rio Grande Basin have varied over the past several decades: wet and drought periods bring associated rises and falls in water levels; agricultural irrigation within the valley has led to seasonal water fluctuations in some areas; and pumping from deep aquifers to supply municipal and industrial water needs has led to significant water-level declines. These processes affect shallow groundwater conditions near the Rio Grande, which in turn impact surface-water/groundwater interaction in the riparian zone. Groundwater elevation characterization in the recent literature has been reviewed to provide some understanding of the nature of change that occurs or has occurred. This section discusses groundwater conditions in the upper portion of the aquifer within and outside of the riparian corridor from south of Belen to the north boundary of the Bosque del Apache, the area represented in the Bernardo and Socorro riparian models (Figure 1.2). 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 on the riparian groundwater models.

5.1 Groundwater Elevations, Belen to San Acacia

The extent of the Bernardo riparian model falls within the southern portion of the Albuquerque basin. Groundwater levels in the southern end of the Albuquerque basin are largely unchanged from their predevelopment levels, especially compared to the magnitude of changes in the vicinity of the city of Albuquerque. Albuquerque Basin groundwater contours in the region covered by the Bernardo model are virtually unchanged from the predevelopment period to 1994 (McAda and Barroll, 2002). While there may be some small localized trends as a result of pumping from municipalities such as Belen, the region covered by the Bernardo model is not subject to the much larger magnitude of pumping that occurs in the Albuquerque area. Data from wells with long-term records do not exhibit significant trends (McAda and Barroll, 2002, observation well SEV-1), and current observations from Bernardo and Sevilleta (UNM ET Tower data) indicate a water table that is only four to eight feet below ground surface, and exhibits significant seasonal influence as a result of river-stage variation.

5.2 Groundwater Elevations, San Acacia to Northern end of Elephant Butte Reservoir

The Socorro riparian model and the Bosque del Apache and Fort Craig model domains fall within the Socorro structural basin (Socorro Basin). Water levels within the Socorro Basin in the Rio Grande valley have changed little since development of irrigation project works in the 1930s. Anderholm (1987) reported data from Bloodgood (1930) and Theis (1938) that indicated that the average depth to water in the valley of the Socorro region was 2.37 feet in the 1920s. After construction of drains and laterals was completed in 1936, water levels in these same observation wells dropped by approximately three feet.

In the past 10 to 20 years, groundwater elevations in wells in the Rio Grande valley do not appear to show a consistent trend toward either increasing or decreasing water levels (SSPA, 2002a). Figure 5.1 illustrates water levels at selected wells in the valley that have been monitored over periods exceeding ten years. Currently, in most valley locations, the water table is less than 10 feet below land surface. However, shallow groundwater elevations in the Socorro valley exhibit seasonal variation, responding to river flows, seasonally-dependent evapotranspiration and irrigation cycles. Continuous records of water levels at shallow observation wells near the river have been collected in recent years by the NMISC; these records (Appendix B) illustrate the occurrence of seasonal water level changes.

Similarly, groundwater elevations in wells in the basin margins have not evidenced a consistent trend towards increasing or decreasing water levels (SSPA, 2002a). However, water elevation changes have been seen in areas subject to municipal and industrial pumping. Continued pumping at these wells at current levels is unlikely to result in significantly greater drawdown. These wells are generally located in high producing zones and relatively near the river; consequently, pumping results in relatively immediate stream depletions and minimal additional drawdown (SSPA, 2002a).

6.0 PRELIMINARY SIMULATIONS AND HYPOTHESIS TESTING, BERNARDO AND SOCORRO MODELS

6.1 Preliminary Model Simulations

Preliminary simulations were made to assess the reasonableness of the model for use in hypothesis testing. The simulations included steady-state runs at various river flow levels, and transient runs in which fall and winter conditions, followed by a spring run-off period, were simulated. Where available, observation well data were compared to the simulated water levels as a check on the model performance. The comparisons indicated that the model performs within a reasonable range. However, as data become available, some fine-tuning of model parameters may be needed prior to application to specific restoration scenarios. The preliminary model simulations are described below.

6.1.1 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, 1,000, 2,000, 3,000, 5,000, 7,000 ad 10,000 cfs). For these simulations, drain surface elevations and general head boundaries were fixed at the values previously described (Sections 3.3.2 and 3.3.3). The following results were reviewed for each simulation:

- Net river seepage (from in-channel and overbank flooded cells)
- Net gains in riverside drains and 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 of trends and conditions. For example, seepage rates were tabulated for selected river and drain reaches, as shown on Table 6.1 for each of the selected river flow magnitudes and considered in light of field measurements, to the extent they are available. Simulated water levels for the 1,000 cfs (referenced to flow at Angostura) steady-state runs of the Bernardo and Socorro models, expressed as a depth from river bottom, are shown on Figures 6.1 and 6.2. None of the data utilized in the comparisons is applicable in a strict sense to a steady-state condition, as seepage rates and water levels respond to the transient nature of the system. And, to replicate a specific set of observation data, the

drain bottoms, water surface elevations and ET rates would need to be matched to conditions measured at the time period of interest. Regardless, these comparisons suggest that the model is functioning in reasonable fashion. The transient simulations, described in the following section, examine model behavior considering some of the time and flow-dependent system components.

6.1.2 Transient Simulations

Transient simulations have been structured to examine model behavior preceding and during spring run-off events in two periods for which observation well data were available. These simulation periods, and the observation well data to which the simulations were compared, are as follows:

- ***2000 – 2001***: Observation well data from two UNM monitoring stations within the Bernardo model.
- ***2003 – 2004***: Observation well data at four RGWS transects within the Socorro model.

To simulate these periods, step-function hydrographs were first prepared from the daily river hydrographs, using the library of flows used to develop the suite of river boundary conditions. These hydrographs are shown on Figure 3.1A and B and are described on Tables 6.2A and B. The hydrographs only roughly approximate the actual progression of flows; finer resolution simulation of the spring pulse may be desired in some applications and should be implemented in such cases. The models were run with a steady-state period at the value of the first step in the step hydrograph, to set initial conditions. The transient simulation followed, with stress periods corresponding to each change in the step-function hydrograph. Available observation wells were associated with model cells, and simulated water elevations were compared to corresponding observation well measurements for the duration of the transient run.

Hydrographs comparing simulated water elevations with measured water elevations for individual observation wells are shown on Figures 6.3 and 6.4. Figure 6.3 illustrates the observed and simulated water level changes for two locations within the Bernardo model during a period of several months prior to and during a spring pulse in 2001. The comparisons are provided for wells within the UNM Bernardo (Bernardo_N and Bernardo_W) and Sevilleta (Sevilleta_C, Sevilleta_E, and Sevilleta_S) observation well clusters. At Bernardo the

comparison indicates that the model is behaving reasonably. At Sevilleta, the model results closely resemble the observations in response and timing; however the simulated groundwater elevation decline beginning in mid-April is of greater magnitude than the observed decline. The Sevilleta wells are located in the southern reach of the Bernardo model in an area for which there is little groundwater elevation control data, particularly at depth. This area also lies beyond the southern boundary of the Albuquerque regional groundwater model, and therefore, required extrapolation of regional groundwater conditions. For these reasons, the simulated elevations from the Sevilleta location (and generally, within the southern reach of the Bernardo model) are considered relative rather than absolute.

Figure 6.4 illustrates the observed and simulated water level changes for the NMISC wells along transects at San Acacia, Escondida, Brown Arroyo and Highway 380. Water elevations are fairly well-matched for observation wells at various depths within the river alluvium (generally, wells with suffix A, B, C correspond to model layers 1, 2, 3, respectively). No suitable observation wells were identified to evaluate groundwater levels in the underlying Santa Fe Formation (model layer 4), and simulated groundwater elevations in layer 4 are largely a function of assumptions reflected in the Socorro regional model. The water elevations taken from the Socorro regional model, given its grid size and regional scale, may not reflect the actual water elevations directly beneath the river alluvium. Monitoring of water levels in the Santa Fe Formation near the river is recommended to support fine-tuning of the riparian groundwater model. While groundwater level elevations in layers 1, 2 and 3 are not highly sensitive to the assumptions regarding water elevations in layer 4, the flow components of the water budget are sensitive to these assumptions and would benefit from further examination.

Table 6.3 identifies the seepage rates at the end of winter, spring run-off and mid-summer for the simulated flow conditions. Seepage runs were not conducted in 2004 and thus a comparison of observed to simulated seepage rates for this period is not possible. However, inspection of seepage rates derived from field measurement in 2000 (Table 2.5b) and similarly derived seepage rates for 2001 (SSPA, 2002b) suggest that the model is under-predicting both river seepage rates and flow to the LFCC. This element of the model should be examined in more detail prior to specific model application in this reach. A robust calibration of the model

requires a dataset including contemporaneous measurement of groundwater elevations, seepage rates and drain elevations (water surface and bed elevation).

6.2 Hypothesis Testing, Base Case

The Bernardo and Socorro riparian models were applied to evaluate hypotheses regarding potential conditions within and surrounding the riparian groundwater zone. The purpose of the hypothesis testing is to illustrate how water levels and river seepage rates are affected under different circumstances, including alternate vegetative, regional water level, antecedent water supply and river channel conditions. These results, while best considered "qualitative" due to the number of assumptions built into the test cases, provide insight into riparian zone sensitivities that may be important to water management and river restoration actions. For this application, the historical runs described in Section 6.1 were used as the Base Case, representative of conditions prior to, during, and following a spring run-off pulse. Modifications were made to various elements of the Base Case to test hypotheses regarding the riparian groundwater system and groundwater/surface-water interactions through the spring run-off cycle.

Analyses utilizing these Base Cases are illustrative, in a general fashion, of what might occur in future spring run-off events, with similar discharges and durations, regional groundwater conditions and drain elevations. However, since these parameters have a strong influence on model results, extrapolation from these results to other cases should be made with caution. In addition, neither drain nor regional groundwater elevations have been varied with season in this project phase. Consequently, model results, particularly for near-drain areas, do not incorporate fluctuations that may occur prior to, during, and following a spring pulse, nor do they necessarily represent average conditions. The transient modeling of drain elevations will be important in some applications and should be implemented in future model runs to improve the simulation of near-drain conditions.

Figures 6.5 and 6.6 illustrate water levels simulated for the Base Case at the end of the spring peak and at mid-summer, expressed as depth below river bottom (calculated as the difference between simulated groundwater elevations and the river bottom elevation corresponding to each model row). Color contours illustrate the depth, with cool colors (greens, blues) representing water elevations above the river bottom elevation and warm colors (yellow,

orange, red) representing water elevations below the river bottom elevation. These figures do not provide information regarding depth to water from land surface, though such figures could readily be generated from model output. Table 6.3 shows the simulated seepage rates for the river, drains and overbank flooded cells at three points in time during the Base Case simulation (end of winter, end of spring run-off, and mid-summer).

6.3 Alternate Vegetative Conditions

As described in Section 2.6, non-native riparian species are assumed in these simulations to utilize water at higher rates than native species; modeled maximum ET rates are four feet per day for salt cedar, versus three feet per day for pure native cottonwood stands (Table 3.4). To conserve water and to attain other environmental benefits, there is interest in restoring native vegetation on bosque lands through replacement of non-native species with native species. Accomplishing a reduction in basin-wide water depletion through this means would benefit the region from a water budget standpoint. Whether such modifications would have local impacts on local water levels and seepage rates is examined through model simulation. The following hypothesis is considered:

> *Hypothesis # 1: Despite the occurrence of reduced water depletion, replacement of non-native with native vegetation will have minimal impacts on groundwater elevations and surface-water/groundwater interaction within the riparian zone.*

To test this hypothesis, an alternate model simulation was structured whereby a change was made to the model ET package; other conditions specified under the Base Case were left unchanged. For the alternate run, areas in the Base Case run assigned vegetation categories with a maximum ET rate of four feet per year, including Salt Cedar, Cottonwood Mixed, and Unknown Vegetation, were re-assigned a maximum ET rate of three feet per year. The curve specifying the ET rate with depth for the Cottonwood Pure vegetation category was then applied in this run for all three of these plant groups. The results of this simulation were compared to the Base Case. Simulated water depletion volumes from ET, under the Base Case and alternative simulations, are shown on Table 6.4. Results indicate that total riparian evapotranspiration is decreased by 20 percent in the Bernardo reach and 25 percent in the Socorro reach as a result of changing all of the non-native riparian vegetation to native cottonwood within the bosque area.

As a result of the decrease in ET, more water is expected to remain in the shallow aquifer. To evaluate this, water elevation differences between the alternate case and the Base Case at mid-summer (end of July) were calculated. Throughout most of the riparian area in the Bernardo model, the groundwater elevation difference between the base case and alternate vegetation simulation is less than half a foot, with higher elevations for the alternate vegetation simulation (Figures 6.7). However, several localized areas with elevation differences of 0.5 to 2.5 feet were observed, most notably the confluence of the Rio Puerco and the Rio Grande, and a region just above the San Acacia Diversion Dam. For the Socorro model, approximately 50% of the active model area experienced groundwater elevation increases of 0.5 feet or less with the transition to native vegetation; the remaining area experienced groundwater elevation increases of 0.5 to 2.5 feet (Figure 6.8). Groundwater level increase in the alternate model run was greatest at the north and south ends of the model grid, below the San Acacia Diversion Dam on the east side of the river, and near San Antonio on the east side of the river. For both models, areas of greatest change correspond to dense monotypic salt cedar stands of significant aerial extent.

Seepage losses simulated with the alternate vegetation assumption are compared on Table 6.5 to those computed for the Base Case at three points in time during the simulation: end of winter; end of spring run-off; and mid-summer. In most sub-reaches, at the end of the spring runoff and in mid-summer, when ET is high, river seepage loss under the alternate vegetation assumption is one to two tenths of a cfs per mile less than the seepage in the same reach under the Base Case assumption. Additionally, seepage into the drains under the alternate vegetation assumption is one to two tenths of a cfs higher than under the Base Case assumption in some sub-reaches for the same period. This is consistent with the slight rise in water table elevations associated with the reduced depletion rates. It is interesting to note that seepage rates for the Socorro model show smaller differences from the Base Case under the alternative simulation than those in the Bernardo model, although groundwater elevation changes in Socorro are greater.

The results of this comparison partially support the hypothesis. As simulated with the Bernardo and Socorro models, change in ET rate in areas covered by non-native vegetation only minimally impacts river/aquifer exchanges. However, groundwater elevation differences

between the simulations were found to be significant in areas where salt cedar presently is extensive. If changes on the order of one half to two feet are important to a particular restoration project, a more detailed simulation could be structured to examine local impacts. Such a simulation would be most useful if refinements included transient specification of drain stage.

6.4 Alternate Regional Groundwater Conditions

Regional groundwater elevations in the Bernardo and Socorro region can fluctuate over four feet annually in response to annual fluctuations in river stage and drain flow. To evaluate the nature of change within the riparian zone due to alternate regional groundwater elevations, alternate model simulations were structured whereby changes were made to the model boundary conditions at the lateral edges of the models, as specified in the GHB package, as well as to drain water-surface elevations, as they also are a reflection of regional groundwater conditions. The other conditions specified under the Base Case were left unchanged. The hypothesis examined in these simulations was specified as:

> *Hypothesis # 2: Water elevations at the boundary of the riparian zone exert strong influence on riparian groundwater elevations and on the magnitude of river seepage.*

If this hypothesis is correct, understanding regional groundwater conditions would be critical in the design of restoration projects where control of ponding conditions or depth to shallow groundwater is needed to meet restoration goals. Furthermore, understanding and potentially managing drain water elevations may be necessary not only for addressing restoration goals, but also for achieving water delivery goals where alternate conveyance via drains or river is occurring.

Two simulations were developed to examine this hypothesis. These are described as:

Low Regional Conditions: Drain stage and groundwater boundary elevations represented in the GHB Package were dropped by 50% of the average drain water depth (1.3 feet in the Bernardo model; 0.6 feet in the Socorro model).

High Regional Conditions: Drain stage and groundwater boundary elevations represented in the GHB Package were raised by 50% of the average drain water depth (1.3 feet in the Bernardo model; 0.6 feet in the Socorro model).

Figures 6.9 through 6.12 illustrate the simulated water elevations, referenced to the river bottom, for each of the models at two points in time: at the end of the spring run-off event, and at

mid-summer (end of July). Each figure displays the depth to groundwater from river bottom elevation for the base, low, and high cases. Throughout the Socorro model and in the top reach of the Bernardo model, the river is losing, as is evidenced by the elevation gradient from the river towards the boundaries, and as is shown on Table 6.6. The lower two reaches of the Bernardo model gain or lose depending on the river flow. For all sub-reaches, the riparian corridor is "drier" with the low regional conditions, in both the late spring and mid-summer. Clearly, this would have implications for the maintenance of shallow groundwater conditions that might be important for some restoration options. Additionally, increased river seepage rates occur when regional boundary conditions are lower. This would impact the maintenance of target river flows for habitat, particularly in low flow periods; also, greater losses throughout the season would have impacts on water delivery via the river channel. Though variable by model reach and by season, the lowered boundary-condition simulation results in increased river seepage losses on the order of 0.3 to 0.6 cfs per mile. For the Bernardo model, inflow to the drains is also reduced 0.2 to 0.3 cfs per mile. Interestingly, the LFCC is less responsive to changes in regional water level, likely because there is already a significant gradient toward the drain and drain seepage is therefore primarily a function of conductance.

These results support Hypothesis #2, that the regional groundwater conditions exert strong influence on riparian groundwater elevations and on the magnitude of river seepage.

6.5 Alternate Antecedent Flow Conditions

As can be seen by examination of historical river flow hydrographs (Appendix D), fall/winter flows can be quite variable. In many years, winter flows are on the order of 1,000 cfs; however, in some years, flows are below 500 cfs, sometimes significantly lower. To examine the impact of low versus high fall and winter flow conditions on hydrologic conditions in the riparian corridor during and after the spring pulse that follows these antecedent conditions, two simulations have been made wherein these conditions are altered from the Base Case. These simulations address the following hypothesis:

> *Hypothesis # 3: The occurrence of long-term low surface water supply conditions, versus normal or high surface water supply conditions, prior to a spring pulse will impact riparian conditions during and following the spring pulse.*

This hypothesis is addressed with two additional runs:

Low Antecedent Condition: For this simulation, the historical run is modified in the first stress period. The first model stress period is a steady state stress which simulates long term average (e.g. in the historical run), dry, or wet conditions during the preceding years. For the low antecedent condition scenario, the initial steady-state flows are reduced from the historical scenario. The Bernardo 2000-2001 simulation is initiated with a steady-state flow of 500 cfs, rather than the historic 1000 cfs; the Socorro 2003-2004 simulation is initiated with a steady-state flow of 100 cfs, rather than the historic 500 cfs. For both, the Base Case spring pulse is unchanged, as are regional groundwater elevations and drain stage.

High Antecedent Condition: For the high antecedent condition scenario, the initial steady-state flows are increased from the historical scenario. The Bernardo 2000-2001 simulation is initiated with a steady-state flow of 2000 cfs; the Socorro 2003-2004 simulation is initiated with a steady-state flow of 1000 cfs. As for the Low Antecedent Condition, the Base Case spring pulse, regional groundwater elevations, and drain stage are unchanged.

Figures 6.13 through 6.14 illustrate the difference in groundwater elevations for these two conditions for both of the new riparian models at the end of spring run-off. The results indicate that there is little difference between the groundwater elevations, following the occurrence of spring run-off of this magnitude, under the low antecedent condition, base case, and high antecedent condition simulations. This conclusion is more readily seen by examination of river seepage rates (Table 6.7), where low-, base-, and high-condition seepage rates averaged over the model stress periods show no difference. Only in the time steps immediately following the initial steady state condition is a small difference in seepage rate evident.

From examination of these simulation results, one would conclude that Hypothesis # 3 is not necessarily true, depending on a number of factors not fully explored in this study. If antecedent conditions do not alter drain stage or regional water levels, they will only impact riparian conditions while they persist, and for a short period of time following their cessation. However, if prolonged antecedent conditions alter boundary conditions, the degree of impact of the antecedent conditions will be a function of the extent to which the boundary conditions have been altered, as well as a function of how persistent the boundary conditions are during and following the spring event. The latter will in turn depend on the magnitude and duration of the spring event. The dynamics of these inter-relationships have not been fully explored with the alternate regional conditions and alternate antecedent conditions simulations presented. Furthermore, evaluation of the persistence of boundary conditions through a spring event would

require augmentation of the model to include a larger region. However, through a combination of examination of historical records and data collection during future spring events, these relationships can be refined and better characterized.

7.0 APPROACH FOR ASSESSMENT OF RESTORATION PROJECTS

The riparian models can be used to evaluate conditions relevant to habitat restoration projects. Evaluations may include depletion analysis, seepage analysis or characterization of seasonal changes associated with the project, for example, depth to groundwater. This process requires assessment of the attributes of the specific restoration site, review of the suitability of site-specific field data to characterize the projected conditions, and modification of model structure as necessary. Depending on specific evaluation goals, focused field data collection may be worthwhile and refinement of various model elements might be pursued.

This section describes how the models can be applied to assess restoration conditions for a hypothetical site that involves the following elements:

- River bank and floodplain modification such that flows above a "primary inundation value" will inundate the project area;
- Construction of a network of new side-channels that will allow for inundation of smaller areas above a "secondary inundation flow level";
- Removal of non-native plant species and replacement with native vegetation.

It is assumed that the goal of the assessment would be to assess the depletion effects of the restoration project in terms of a difference between the existing condition or a no-action future condition; and, to assess the seasonal changes in groundwater levels and seepage conditions associated with the planned changes under various flow regimes. Assuming that the restoration project would be located between the river and riverside drains, model modifications would be made to reflect altered overbank, side-channel, and vegetation conditions within the restoration area. Approaches for these changes are described below. For some analyses, it may be important to assess the potential change in regional groundwater elevations and associated model boundary conditions, i.e., water level surface elevations in drains. Aside from additional data needs, these latter changes would be straightforward, simply requiring corresponding changes in input to the model packages.

7.1 MODFLOW River Package Modifications

The riparian model river packages consist of three cell groups: in-channel cells, overbank cells, and drain cells. For the restoration simulation, a fourth cell group, consisting of all the cells falling within the restoration project area, would be added to the river package.

Additional cell designations in the river package for the restoration simulation would include one of two types, lowered floodplain cells, or side-channel cells.

- The designation of specific model cells as side-channel cells should be based on the geometry of the restoration project. The side-channel cell bottom elevation should be set equal to the river water surface elevation obtained from FLO-2D for the secondary inundation value. The side-channel water surface elevations, for flows in excess of the secondary inundation flow value, should be set equal to the river water surface elevation corresponding to the FLO-2D output for corresponding library flows.
- Once side-channel cells are designated, the remaining cells within the restoration area should be designated as lowered floodplain cells. The land surface elevation for these cells should be set equal to the river water surface elevation obtained from FLO-2D for the primary inundation flow value. For flows over the primary inundation flow level, water surface elevation for the lowered floodplain cells should be set equal to the river water surface elevation as obtained from corresponding FLO-2D runs.

Conductance for both types of cells is calculated as:

$$C = \frac{L * W * K_v}{M} \qquad \text{Equation 7.1}$$

where:

C is floodplain/side-channel bed conductance (ft^2/day);
L is length of the flooded/wetted area within the given cell (ft);
W is width of the flooded/wetted area within the given cell (ft);
K_v is the floodplain/side-channel vertical hydraulic conductivity (ft/day);
M is the floodplain/side-channel bed thickness (ft).

Given the approach described, the entire project area is lowered to a land surface elevation corresponding to the water surface elevation of either the primary or secondary inundation flow; however, if greater detail in representation is desired, the land surface elevation of the restoration cells can be set cell-by-cell as desired. As with other simplifying assumptions,

refinement should be considered depending on the specific goals and needs of restoration project evaluations, and on the availability of additional site-specific information.

7.2 MODFLOW Riparian ET Package Modifications

The riparian ET package incorporates information on land surface elevation and percentage cover by plant group for each model cell. The model can be structured to compare the existing condition and the restoration condition; or, if desired, to compare a future no-action condition with the restoration condition, if the existing and the future no-action condition are expected to differ. For the cells falling within the restoration area, land surface elevation specified within the riparian ET package should be modified to reflect the lowered elevations under project conditions, consistent with values as described above. Handling of the modified vegetation distribution is more difficult and requires careful analysis of site-specific conditions.

The designation of vegetation coverage for the existing condition could be taken as presently input for the baseline simulations, however, this approach may not yield the sensitivity or accuracy needed for a depletion analysis to support water rights questions. For example, the data reviewed for this study do not consistently or demonstrably support a single value of evapotranspiration for flooded cottonwood as compared to salt cedar that can be relied upon for a water rights analysis without further, site-specific, consideration. Although simplifying assumptions may be required due to lack of site-specific data, or may be appropriate for some evaluations, the assignment of evapotranspiration rates warrants careful analysis.

As the models are presently configured, a correction is required to characterize open water evaporation from the off-channel flooded cells within the restoration area due to differences in handling of open water evaporation from river and off-river cells. Additionally, a correction is needed to address the incremental difference between the open water evaporation rate and the assigned vegetation evapotranspiration rate for the off-channel cells inundated during the flows above the primary inundation flow value. As this incremental difference typically is small, and because the number of days of such inundation is limited, this correction is relatively small, nevertheless, it should be considered.

7.3 Transient Simulation of Restoration Conditions

After setting up input files for the modified restoration conditions, transient simulations can be made to illustrate a range of changes that would be associated with the restoration assumptions given hypothetical spring runoff pulses or other flow sequences of interest. For example, the restoration project could be analyzed with the step-function hydrographs established for the baseline simulations as occurred in 1993-1994, the 2000-2001, and the 2003-2004. However, for some project evaluations, it may be necessary to further refine the step-function hydrographs by FLO-2D modeling of conditions at intermediate flow levels.

Transient simulation results can be compared with those developed for a baseline condition, either taken as the existing condition, or as a no-action future condition, as appropriate to the restoration evaluation. Model results will provide river, drain, overbank, and project area seepage; and, groundwater elevations, for the simulated conditions. These results can be examined in terms of various water balance elements, for example, the transfer of surface water to groundwater, flow out of the riparian groundwater system into the regional groundwater system, and increase in evapotranspirative loss over the course of the given model simulation.

8.0 IMPLICATIONS FOR WATER MANAGEMENT AND RESTORATION ACTIVITIES

The riparian model simulations conducted in this second project year further illustrate the dynamic nature of riparian zone behavior, with inter-relationships among environmental components including groundwater, surface water and vegetation. These dynamics have implications for both water management and restoration activities. Insights gained from the model simulations relevant to water management and restoration projects are discussed in this section, along with a discussion of how the riparian models might be applied to support these activities.

8.1 Restoration Project Planning, Design and Operation

The design of river or riparian restoration projects typically includes objectives related to hydrologic characteristics, for example, the occurrence and persistence of shallow saturated soil conditions, or the maintenance of minimum river flows. Generally understood to be spatially and temporally variable, these conditions can be observed from field studies at times and locations of interest; such observations may then be used to make inferences about conditions following restoration activities. However, there may be processes impacting observations, not evaluated by the investigator, that severely affect the transferability of observed conditions to an altered environment. Such processes include those investigated in the hypothesis testing simulations described in Section 6, for example, regional groundwater conditions. The riparian models developed to date, though requiring refinement to support specific restoration design questions, illustrate sensitivities that may be important in restoration planning. The simulations provide a basis for understanding seasonal changes in seepage rates and shallow groundwater conditions that may be critical to the success of a river or bosque restoration project. The primary insight derived from the simulations, then, is that the riparian environment is a dynamic environment impacted by multiple processes that manifest differently under different conditions.

The riparian models can be used in a number of ways to support restoration activities. These include:

- Site selection/assessment: Simulations can be conducted to assess general characteristics, for example, the likelihood of a reach being relatively “wet” vs. relatively “dry” under a range of conditions. For this type of simulation,

particular combinations of potential conditions can be specified and the response of the riparian zone may be evaluated to identify reaches suitable for restoration projects. Assessed characteristics may include anticipated ranges of river seepage, an important parameter to understand for the maintenance of river flows that are judged desirable for aquatic species. Similarly, the depth to water below land surface and maintenance of desired shallow groundwater conditions in the riparian zone can be assessed with regard to Southwest Willow Flycatcher habitat.

- Feasibility studies: Alternate restoration approaches can be simulated and assessed to identify whether the project is likely to achieve hydrologic objectives under an expected range of potential climate and water supply conditions.

- Project design: Projects that have been selected for design and construction can be modeled to fine-tune design elements. For example, modified river bed or drain elevations would have a large impact on hydrologic conditions within the riparian zone. Similarly, channel configuration may be important to the maintenance of saturation in particular localized areas, or for the control of river seepage rates. A specific project site can be modeled with a range of design parameters to identify combinations that are most favorable under conditions of interest

- Project monitoring and operations/maintenance: Hydrologic data pertaining to a specific project can be monitored following project start-up and used to refine model characteristics for the project vicinity. Then, using the refined model, change under forecasted or potential future conditions may be simulated, possibly providing an opportunity to identify and implement additional project controls to improve project success under changing conditions.

Depending on the nature of a specific application, the riparian models developed and refined under the second year of this project can be used with varying degrees of additional refinement. To support site selection and assessment, relatively limited refinements would be needed. This might include incorporation of transient drain elevations to improve the capture of seasonally significant processes. Appropriate levels of model refinement increase through the progression from assessment to feasibility study to design. Through this progression, model refinement should be supported with increasing levels of locally relevant data. Useful data would include reach-specific paired river and drain seepage runs, and concurrent water-level monitoring in shallow piezometers within the reach. Drain and river bottom elevations should also be surveyed to increase the spatial resolution of these data within the area of interest.

8.2 Water Management

Key among water management priorities is the efficient conveyance of water to meet demands, whether the demand is driven by urban, agricultural, environmental or interstate compact needs. In this discussion, "efficient conveyance of water" is broadly defined and without specific reference to purpose or place of use. However, of importance are the minimization of waste and the unwanted transfer of water from a conveyance system en route to its destination. Without making a judgment regarding what is or isn't waste, or what system exchanges are desirable, it is assumed that water use and delivery goals can be identified. Once goals are identified, knowledge of riparian system dynamics can be applied to improve conveyance efficiency. For example, it might be decided that in various reaches, river losses are desirable because they support an important environmental process; alternatively, it might be decided that river losses should be minimized to support flow conditions for fish habitat or to bolster downstream flows in order to meet flow requirements.

The efficient conveyance of water requires knowledge of river and drain seepage losses/gains under alternate supply, regional and routing conditions. While river and drain seepage losses/gains can be quantified through field investigation, it would be impractical and expensive to conduct enough field investigations to characterize the losses/gains under all potential conditions that may be important to water management. For example, river seepage losses are dependent on concurrent drain stage and other conditions. Should these conditions vary due to modified system operations, groundwater elevations or other processes, variation of river seepage rates will also occur. The ability to transfer knowledge gained under one set of conditions to another set of conditions can be rapidly assessed using modeling tools such as the riparian models, assuming that a sufficient range of measured information is available for model calibration. Improved understanding of riparian system dynamics and relationships through modeling analysis might be applied to the following situations:

- Quantification of increased depletion (identification of water needs) for river or bosque restoration projects;
- Quantification of changes in seepage loss and return flows under altered river or bosque conditions (i.e., what portion of river losses are captured by drains, and how timing and location of returns are modified);

- Assessment of changes in river losses under alternate water conveyance alternatives, for example, if drains are more heavily utilized as conveyance channels for irrigation water;
- Assessment of changes in river losses under different river operation scenarios, i.e., as a function of flow magnitude or timing of delivery.

The riparian models developed and refined during the second year of this project can be used to explore sensitivities in these areas under alternate management or operational scenarios. However, the results of such simulations will improve in accuracy with additional model refinement. Additional refinements may also be desired to support the evaluation of specific water management scenarios.

The incorporation of additional data into the model will improve its predictive value. While focused data collection activities may be needed for specific evaluations, some general recommendations can be made for data to support the understanding of system behavior relevant to water management activities. General data collection recommendations include:

- Continue to expand the network of shallow groundwater well transects across the river where such transects are not presently in place;
- Continue monitoring with automatic data recorders shallow wells at the river transects;
- Install and monitor deeper wells into the upper zone of the Santa Fe Group (i.e., 150 to 200 foot depth range) in the near-river zone to provide local control on "regional, deep" groundwater conditions;
- Obtain drain bed elevations at more closely spaced measurement points;
- Install drain and river stage gages at multiple paired locations;
- Update river bottom elevations at more closely spaced measurement points; and,
- Conduct paired river and drain seepage runs under a variety of seasonal and flow conditions, with concurrent monitoring of shallow groundwater elevations.

The incorporation of such additional data into the riparian groundwater models would improve their physical representation of the hydrologic system and their utility in water management.

The riparian groundwater models, as developed and refined during the second year of this project, provide a tool for evaluating water management alternatives that are sensitive to surface-water/groundwater interaction in the riparian zone. The application of the models to such questions may identify improvements in conveyance and water delivery efficiency in the river/drain system that would benefit the region in meeting diverse demands with a limited water supply.

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