SIERRA VISTA WATER RECLAMATION FACILITY GROUNDWATER MODELING STUDY

Prepared for
City of Sierra Vista, Arizona

June 2009

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Prepared for
City of Sierra Vista
1011 North Coronado Drive
Sierra Vista, Arizona 85635

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Brown and Caldwell Project #: 134159

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LIST OF ACRONYMS

°F	degrees Fahrenheit
ADWR	Arizona Department of Water Resources
AFY	acre-feet per year
amsl	above mean sea level
ARM	absolute residual mean
AWC	Arizona Water Commission
AWPF	Arizona Water Protection Fund
BC	Brown and Caldwell
BLM	Bureau of Land Management
BOR	Bureau of Reclamation
cfs	cubic feet per second
DEM	digital elevation model
ESI	Environmental Simulations, Inc.
ET	evapotranspiration
ft/day	feet per day
ft^2/day	square feet per day
Ft/yr	Feet per year
GIS	Geographic Information System
GMG	Geometric Multi-Grid
GWSI	Groundwater Site Inventory
m/day	meters per day
mgd	million gallons per day
NAD	North American Datum
NRCS	Natural Resources Conservation Service
U.S.	United States
USDA	United States Department of Agriculture
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
WRF	Water Reclamation Facility

1. PROJECT DESCRIPTION

The City of Sierra Vista (City) has contracted with Brown and Caldwell to provide professional groundwater modeling services to support conditions of the United States Bureau of Reclamation (BOR) Demonstration Recharge Project, Cooperative Agreement No. 00-FC-32-0030, requiring documentation of the impacts of recharge from their Water Reclamation Facility (WRF) (Figures 1-1 and 1-2). Funding assistance for the construction of the Sierra Vista WRF was provided by the BOR and the Arizona Water Protection Fund (AWPF). A condition of the BOR cooperative agreement was to develop a regional groundwater model (Sierra Vista Model) that would be capable of simulating changes in regional groundwater levels and baseflows in the San Pedro River due to recharge activities from the Sierra Vista WRF every 5 years from 2007 until 2022, and in 2040. A condition of the AWPF agreement, independent of the groundwater modeling aspect, was to establish a monitoring program to create a baseline for hydrology and vegetation, and assess the impacts of recharge over time.

Key objectives of the groundwater modeling performed for this project include assessing the effects of the WRF recharge on the regional aquifer system and estimating the potential for recharge to maintain and augment baseflow in the San Pedro River. The final model product will also serve as a tool to assist the City with implementing water strategy plans to meet the City's water resource needs, as well as managing and protecting regional groundwater reserves and flows along the San Pedro River.

This report details the results of the work to develop the Sierra Vista Model as well as the initial model simulations as stipulated by the BOR cooperative agreement.

1.1 Project Background

The Sierra Vista WRF is located approximately 3.5 miles from the San Pedro River and is designed to treat up to 4.0 million gallons per day (mgd) of reclaimed water. Approximately 50 acres of wetlands are used to treat the water to tertiary standards before being recharged via 11 artificial recharge basins (Figure 1-2).

The WRF is a BOR demonstration project, and was designed to create a mound of water that would: 1) slow the eastward advance of the groundwater "cone of depression" toward the San Pedro River; and 2) sustain baseflows in the San Pedro River. The prevailing assumption with respect to the impact of WRF recharge has been that it will induce a local rise in groundwater levels, help maintain regional aquifer conditions, and eventually augment flows in the San Pedro River, helping maintain baseflows and the associated riparian habitat.

A monitoring program to document baseline conditions was instituted in 2002; initial results are summarized in the report titled *City of Sierra Vista Water Reclamation Facility Final Monitoring Report* (Fluid Solutions, 2002). The baseline established in 2002 provides a point of comparison for both monitoring (recharge volumes, water level rise, vegetation growth, etc.) and predictions of future impacts. Monitoring data from wells located within the recharge basins indicate that groundwater levels have increased by a maximum of 43 feet since 2002. These data demonstrate a local rise in groundwater (fulfilling one of the project requirements); however, a groundwater model is required to adequately assess the long-term, regional impacts of recharge. The groundwater modeling phase of work was designed to utilize data from the monitoring program and build on the existing body of knowledge from previous studies.

A number of groundwater modeling and modeling-related studies have been completed in the region, including the Arizona Department of Water Resources' *Groundwater Flow Model of the Sierra Vista Subwatershed of the Upper San Pedro Basin* (Corell et al., 1996) (ADWR Model) and the United States Geological Survey (USGS) *Ground-Water Flow Model of the Sierra Vista Subwatershed and Sonoran Portions of the Upper San Pedro Basin, Southeastern Arizona, United States, and Northern Sonora, Mexico* (Pool and Dickinson, 2007) (USGS Model). The USGS model incorporates results from extensive hydrologic investigations and monitoring performed from the mid-1990s through 2004, and is the most comprehensive tool available to support the purposes and objectives of the project. This model is a fully three-dimensional, regional groundwater flow model of the aquifer system and builds upon all previous studies and models of the system, including the ADWR Model.

1.2 Project Approach

To address the key objectives of this study, Brown and Caldwell integrated hydrogeologic monitoring data collected in the vicinity of the WRF into the framework of the USGS model and created an updated model – the Sierra Vista Model – capable of accurately simulating local scale hydrogeologic conditions near the Sierra Vista WRF.

Specific tasks contained within the Scope of Work for the project (revised on October 29, 2008) are as follows:

- Task 1 – Project Management
- Task 2 – Data Collection and Organization
- Task 3 – Model Review and Analysis
- Task 4 – Conceptual Model
- Task 5 – Revised Numerical Model Development
- Task 6 – Validation/Calibration
- Task 7 – Predictive Simulations
- Task 8 – Modeling Final Report
- Task 9 – Vegetation Assessment (Sub-Consultant task)
- Task 10 – Wildlife Assessment (Sub-Consultant task)
- Task 11 – Vegetation/Wildlife Assessment Final Report (Sub-Consultant Task)

Modeling tasks 1 through 8 have been performed by Brown and Caldwell and are summarized in this final report. Tasks 9, 10, and 11 are independent of the groundwater modeling tasks and were assigned to SWCA® Environmental Consultants under subcontract to Brown and Caldwell. The Vegetation and Wildlife Assessment Final Reports have been completed and were submitted to the City in July of 2008.

To provide the background for the technical details of model development and results discussed in later sections of this report, summaries of the hydrologic setting of the study area and previous modeling studies performed for the region are presented in Sections 2.0 and 3.0, respectively.

2. HYDROLOGIC SETTING

The Upper San Pedro Basin (Basin) comprises approximately 2,600 square miles in southeastern Arizona and portions of northern Mexico (Figure 1-1). The Basin extends from Cananea in Sonora, Mexico north to “The Narrows”, a bedrock constriction located approximately 11 miles north of Benson, Arizona. From north to south the Basin is divided into three distinct regions: the Benson subwatershed, the Sierra Vista subwatershed and the Sonora, Mexico region.

The study area for this project’s Scope of Work is centered on the Sierra Vista subwatershed, which extends north from the United States (U.S.) - Mexico International Border to Fairbank, Arizona (Figure 1-1). The 1996 ADWR Model simulated only the Sierra Vista subwatershed (Correll, 1996); whereas, the USGS Model expanded the model domain to the south, adding the Sonora, Mexico region and surrounding areas (Pool and Dickinson, 2007).

2.1 Geology

The study area is located in the Basin and Range physiographic province typified by uplifted, block-faulted mountains and basins forming within the grabens. Sediments deposited within the region are of Miocene through early Pleistocene age. The earliest, oldest sediments form the Pantano Formation, which is a semi-consolidated conglomerate. Above the Pantano Formation are alluvial sediments which are generally broken into three categories: basin-fill, terrace deposits, and stream alluvium. The basin-fill is broken into a lower and upper basin-fill, with the lower basin-fill consisting of Miocene to Pliocene interbedded gravels and sandstones and the upper basin-fill consisting of Pliocene to Pleistocene-aged weakly cemented clays, silts, sands, and gravels. The terrace deposits were formed in the mid-Pleistocene and mark the location of the ancestral San Pedro River as it underwent downcutting and extension from the base of the mountains. The sediments of the terrace deposits are typified by poorly-sorted gravels, sand, and clay. The stream alluvium deposits are the youngest sediments and are comprised of sand and gravel from the high-energy depositional environment of the modern San Pedro River (Leenhouts, 2006).

Though all four units are water-bearing, the upper and lower basin-fill sediments comprise the primary regional aquifer system. The Pantano Formation can be a locally important water-bearing unit providing water through fractures in the vicinity of Sierra Vista (Pool and Dickinson, 2007); however, the lower-basin fill consistently bears water throughout most of the Basin. Descriptions and cross sections of the primary geologic units of the regional aquifer system are provided in Pool and Dickinson (Table 1 and Figure 3, 2007).

2.2 Climate

The climate within the study area is semi-arid to arid. Due to orographic effects and the range in elevations, there are large variations in precipitation, temperature, and vegetation patterns within the Basin. Elevation ranges from approximately 3,300 feet above mean sea level (amsl) along the San Pedro River to 9,500 feet amsl in the mountains. Temperatures range from a mean maximum temperature of 80 degrees Fahrenheit (°F) to a mean minimum of 45°F (Leenhouts, et al, 2006).

Trends in precipitation were analyzed in a study by Pool and Coes (1999), which reported an average of 16.1 inches of precipitation based on data collected from 1956 to 1997 at four precipitation stations. Additionally, the region experiences two "wet" seasons. The summer wet season occurs between the months of June through October, and the winter wet season occurs between the months of November through February. A dry season usually occurs during the months of March through May (Pool and Coes, 1999).

2.3 Surface Water

The study area is drained by the San Pedro River which flows northward from its headwaters in Canenea, Mexico through the central portion of the Basin approximately 4 miles east of the City of Sierra Vista. The San Pedro is one of the few unregulated, perennial rivers remaining in Arizona. Important tributaries to the San Pedro River include the Babocomari River, located to the north of Sierra Vista, and the Rio Los Fresnos, located in the Mexican portion of the Upper San Pedro Basin (Figure 1-1). The San Pedro River and its two main tributaries are reported to have perennial reaches, although the perennial reaches of the Rio Los Fresnos are not specifically identified. The San Pedro River has perennial flows near Hereford, Arizona, and between State Highway 90 and Boquillas (Pool and Dickinson, 2007). Perennial flows on the Babocomari River occur between the Mustang Mountains and the Huachuca Mountains, as well as approaching the confluence with the San Pedro River. All other washes and drainages to the San Pedro River are considered to be ephemeral.

Baseflows of the San Pedro River vary seasonally and are dependent upon precipitation, surface water use, and groundwater withdrawals with summer baseflow generally lower than winter baseflow (Pool and Coes, 1999). The USGS Charleston stream gage (Gage 9471000) is located north of the WRF, and has the longest period of record; the average annual baseflow for the summer period of 1936 through 1997 was calculated at 2.9 cubic feet per second (cfs), versus 10.9 cfs calculated for the corresponding winter period (Pool and Coes, 1999).

2.4 Land and Water Use

Prior to development, water use was primarily for livestock and mining activities. During the mid-1900s, water use was generally agricultural in nature. By the late 1900s, water use had shifted to satisfy industrial, mining, and domestic demands for a growing population (Pool and Dickinson, 2007).

2.5 Hydrogeology

As noted above, the primary regional aquifer is comprised of the upper and lower basin-fill deposits that overlie the Pantano Formation. In the Sierra Vista subwatershed (Figure 1-1), the thickest package of these deposits is located within a structural depression on the eastern boundary of the City. The depression trends south to north along the San Pedro River, then curves away from the river to the northeast at roughly the midpoint of the subwatershed. Total saturated thickness of these units within this depression ranges from 1,300 to 1,640 feet (400 to 500 meters). Moving westward from this structural depression, the aquifer thins rapidly with a thickness less than approximately 330 feet (100 meters) on the western boundary of the model domain.

The predominant, regional direction of groundwater flow is from south to north, with smaller scale groundwater gradients moving away from localized recharge sources and/or toward localized groundwater outflow features such as wells (Pool and Dickinson, 2007, Figure 5). The system is assumed to be closed with respect to subsurface inflows, implying that no groundwater enters from adjoining basins. Natural recharge is primarily derived from precipitation in the higher elevations that enters the aquifer system as mountain front recharge, and from losing reaches along the San Pedro, Babocomari and Los Fresnos rivers. Groundwater flows through the system toward natural discharge locations at lower elevations, including: springs, seeps, rivers, and evapotranspiration (ET) associated with riparian vegetation. Groundwater also leaves the study area as underflow to the Benson subwatershed to the north.

In the vicinity of the Sierra Vista WRF, groundwater gradients are directed radially away from a groundwater mound located underneath the WRF recharge basins and constructed wetlands. Groundwater flow emanating from the northern and eastern boundaries of the WRF proceeds toward the course of the San Pedro River to the east. Flow emanating from the western boundary of the WRF migrates toward a cone of depression located several miles to the west. Southerly groundwater flow from the WRF approaches an area of flatter groundwater gradient and diverges to both the east and west. Moving away from the WRF recharge basins, water level elevations fall off rapidly in all directions. To the west and south of the facility depths to water generally increase with distance. Moving east and north of the facility, land surface elevations decline due to the presence of the San Pedro River channel; causing depths to water to actually decrease and groundwater to daylight at springs, seeps and the bed of the San Pedro River. Based upon water level measurements recorded by ADWR, depths to water increase substantially and reach magnitudes greater than 100 feet within two miles west of the recharge basins. These greater depths to water are caused by both an increase in land surface elevations as well as the influence of the historic cone of depression. Prior to recharge activities at the WRF, a groundwater "ridge" was present in this area, characterized by a relatively flat groundwater gradient. Although there was not the radial flow pattern associated with the current groundwater mound underneath the WRF, flow generally proceeded either eastward to the San Pedro River corridor or westward toward the cone of depression. Additional information related to local groundwater conditions at the Sierra Vista WRF is provided in Sections 5.0 and 7.0.

3. PREVIOUS MODELING EFFORTS

Previous numerical groundwater modeling efforts in the Upper San Pedro Basin have contributed substantially to the present-day understanding of the system. Brown and Caldwell was tasked with a review of the major models available for the region to select the best tool for the key objectives and goals of this project. Studies of note that were evaluated for this work include:

- Arizona Water Commission, 1974. *Status Report of a Study of the Adequacy of the Water Supply of the Fort Huachuca Area, Arizona, in Report on Water Supply, Fort Huachuca and Vicinity, Arizona.* U.S. Army Engineers District, Los Angeles.
- Freethey, G.W., 1982. *Hydrologic Analysis of the Upper San Pedro Basin from the Mexico-United States International Boundary to Fairbank, Arizona.* U.S. Geological Survey Open File Report 82-752.
- Vionnet, L.B. and Maddock, T., 1992. *Modeling of Groundwater Flow and Surface Water/Groundwater Interactions in the San Pedro River Basin-Part I-Cananea, Mexico to Fairbank, Arizona:* Tucson, University of Arizona, Department of Hydrology and Water Resources, HWR No. 92-010.
- Correll, Steven W.; Corkhill, Frank; Lovvik, Daryl; and Putman, Frank, 1996. *A Groundwater Flow Model of the Sierra Vista Subwatershed of the Upper San Pedro Basin – Southeastern Arizona.* Arizona Department of Water Resources. Modeling Report No. 10. December 1996.
- Pool, D.R. and Dickinson, Jesse, 2007. *Ground-Water Flow Model of the Sierra Vista Subwatershed and Sonoran Portions of the Upper San Pedro Basin, Southeastern Arizona, United States, and Northern Sonora, Mexico.* U. S. Geological Survey Scientific Investigations Report 2006-5228.

The first study in this series was completed by the Arizona Water Commission (AWC) in 1974 to analyze water availability for Fort Huachuca, Arizona. Modeling efforts consisted of a one-layer, one-mile-square discretized grid to simulate unconfined aquifer conditions with mountain front recharge. The boundaries for this model domain extended from the Mexican border to St. David, Arizona.

Freethey developed a conceptual hydrogeologic flow model of the Upper San Pedro Basin from Mexico to Fairbank, Arizona in 1982. This groundwater flow model included two layers representing an upper unconfined aquifer and a lower confined aquifer. Model grid spacing was variable, ranging from 0.6 to 1 mile.

Several groundwater models based on Freethey (1982) have been developed. All of these models used Freethey's assumptions as a basis, although they extended the simulation period and contained more detailed model discretization. The models developed by Vionnet and Maddock (1992) and the ADWR Model (Correll et al., 1996) are of particular note. Vionnet and Maddock (1992) constructed a MODFLOW model based on the conceptual model from Freethey with the inclusion of the stream-aquifer interaction package, updated pumping and refined aquifer parameters. In 1996, ADWR published the *Groundwater Flow Model of the Sierra Vista Subwatershed of the Upper San Pedro Basin* (Corell et al., 1996). The stated purpose for this groundwater model was to expand the active model domain and produce an analytical tool to quantify how municipal and agricultural pumping would impact flow in the San Pedro and Babocomari Rivers, associated riparian areas, the floodplain alluvial aquifer, and the regional aquifer. The ADWR model simulated only the Sierra Vista subwatershed portion of the Basin.

In 2007, the USGS completed a new model that simulated both the Sierra Vista subwatershed and the Sonoran region (Mexico) of the Upper San Pedro Basin using MODFLOW-2000 (Harbaugh, 2000). The USGS Model simulation began with pre-development, steady-state conditions and ended with calibrated, transient conditions through March 2003. Using more recent sources of data, the USGS Model refined and advanced the previous modeling work by including: a more detailed three-dimensional model discretization based on lithology, updated pumping demands, more refined numerical representation of transient stream-aquifer interactions, and updated rates for recharge and seasonal ET.

3.1 ADWR Sierra Vista Subwatershed Groundwater Model

The ADWR Sierra Vista Subwatershed Groundwater Model (ADWR Model) (Correll et al., 1996) was developed with the MODFLOW 1988/1996 computer code (Harbaugh and McDonald, 1996), and has an expanded model domain relative to earlier modeling efforts. The ADWR Model was developed to provide a numerical tool to answer questions relating to groundwater conditions in the floodplain and regional aquifer system, and the impact of groundwater usage and recharge upon flows in the San Pedro and Babocomari Rivers.

3.1.1 ADWR Flow Model Construction

As seen on Figure 3-1, the ADWR Model extends northward from approximately 6 miles south of the U.S.-Mexico boundary to Fairbank, Arizona and is bounded by the Huachuca Mountains to the west and the Mule Mountains to the east. Individual model grid cell sizes range from 0.06 square miles (40 acres) to 0.25 square miles (160 acres). Higher grid cell resolution is concurrent with the course of the San Pedro River, areas of high groundwater gradients, and the Sierra Vista/Fort Huachuca regions. The grid is oriented to be roughly parallel with the northern reaches of the San Pedro River. Model specifications are provided in Table 3-1.

Table 3-1. Specifications of the ADWR Groundwater Model of the Sierra Vista Subwatershed in the Upper San Pedro Basin

Model Characteristics	Specifications
Active Model Domain	~500 square miles, ~320,000 acres
Units	Time: Days Length: Feet
Coordinate System	UTM NAD83, Zone 12N GIS: lateral units in meters, vertical units in meters
Model Grid	72 rows by 67 columns, 14,472 total cells, 5,830 active cells Origin X: 1,877,147.5361 Y: 11,339,307.743 Rotation: 16.68 degrees (counterclockwise)
Cell Size	Variable mesh. 1,320 to 2,640 feet 0.25 mile to 0.5 mile

Table 3-1. Specifications of the ADWR Groundwater Model of the Sierra Vista Subwatershed in the Upper San Pedro Basin

Model Characteristics	Specifications
Layering – 3 Layers	Layer 1: Floodplain alluvium. LAYCON = 1 (Unconfined/Confined) Layer 2: Upper basin-fill and the uncemented portions of the lower basin-fill. LAYCON = 3 (Unconfined/Confined, T Varies) Layer 3: Pantano Formation and the cemented portions of the lower basin-fill. LAYCON = 3 (Unconfined/Confined, T Varies)
Hydraulic Parameters	Layer 1: K = 40 ft/d Sy = 0.15 Sc = 0 Layer 2: K = 0.1 to 25 ft/d Sy = 0.08 Sc = 0.0001 Layer 3: K = 0.1 to 20 ft/d Sy = 0.08 Sc = 0.0001
MODFLOW Packages	MODFLOW 1996, Basic, BCF, Output Control, SIP, Well, Stream, Recharge, ET
Simulation Time and Stress Periods	1940 – Steady state model with a single stress period 1941 to 1990 – Fourteen transient stress periods, ranging from annual to 13 year stress periods. Time step multiplier = 1
Recharge	0.04 to 1.3 ft/yr representing mountain front recharge and underflow
Wells	860 prescribed flux boundary condition cells
Boundary Conditions	Constant Heads along the Northern Boundary representing underflow to the Benson subwatershed and recharge cells along the southern boundary representing underflow into the Sierra Vista subwatershed
Initial Conditions	Calibrated Steady State heads for 1940
Solution Method	Strongly Implicit Procedure (SIP)

The model is vertically discretized into three layers representing the primary hydrostratigraphic units as defined by ADWR. Model Layer 1 represents the floodplain alluvium associated with the San Pedro and Babocomari Rivers. Model Layer 2 represents the regional aquifer, comprised of upper basin-fill sediments and uncemented portions of the lower basin-fill. Model Layer 3 corresponds to the less permeable Pantano Formation and the cemented portions of the deeper, lower basin-fill.

Inactive (or "no flow") cells were applied to "hardrock", or relatively impermeable areas corresponding to the mountainous regions bounding the model domain and also along the bulk of the northern boundary where flow is parallel to the edge of the model (from west to east). Constant head cells were used to simulate the underflow out of the model into the Benson subwatershed to the north. Mountain front recharge was applied to the entire western boundary, the northern slopes of the San Jose Mountains to the southeast, and along the Mule Mountains and the Tombstone Hills to the east. Recharge was also applied to the southwestern edge of the model domain to represent underflow derived from natural recharge within Mexico.

Transmissivity values in the ADWR Model range from 20 square feet per day (ft^2/day) to 14,000 ft^2/day. Specific yield for Layers 1, 2, and 3 were 0.15, 0.08, and 0.08, respectively. Storage coefficient was assigned a constant value of 1×10^{-5}. These values are within the range of commonly used hydraulic parameters for regional scale groundwater basin models in Arizona.

A steady-state simulation was performed and was calibrated to an interpreted 1940 water level map. The resulting steady-state head array was then used as initial conditions for the transient simulation. The transient base model simulates groundwater conditions between 1941 and 1990 and is comprised of 14 temporal stress periods of various lengths of time. The model was used in a series of predictive simulations reflecting several potential water management scenarios for the time period between 1990 and 2030. A baseline predictive simulation was also run, which assumed continued pumping demands at 1990 rates with phasing out of agricultural pumping in the Palominas/ Hereford area by the year 2000.

3.1.2 ADWR Model Import and Review

Original model files were obtained from ADWR and the files were imported into Groundwater Vistas software for pre- and post processing (Environmental Simulations, Inc. [ESI], 2008). Brown and Caldwell successfully reproduced the results obtained by ADWR, as evidenced by the water budget comparison (Table 3-2) and by comparison of simulated water levels with ADWR digital model output within a Geographic Information System (GIS) environment.

Table 3-2. Water Budget Comparison for ADWR and Brown and Caldwell Simulations of ADWR Sierra Vista Subwatershed Model (AFY)

	ADWR Model 1941 (Stress Period 1)	BC Import 1941 (Stress Period 1)	ADWR Model 1990 (Stress Period 14)	BC Import 1990 (Stress Period 14)
Inflows (AFY)				
Recharge	19,000	19,001	19,000	19,001
Stream	3,812	3,418	4,283	3,886
Storage	1,514	1,514	7,299	7,139
Total	24,326	23,933	30,582	30,026
Outflows (AFY)				
Constant Head	441	441	436	436
Pumping	2,754	2,754	10,693	10,693
Evapotranspiration	8,470	8,469	7,587	7,620
Stream	11,875	11,472	9,941	9,553
Storage	791	800	1,925	1,727
Total	24,331	23,936	30,582	30,029

AFY = acre-feet per year
BC = Brown and Caldwell

The match between the simulated water budget inflows and outflows (24,326 versus 24,331 acre-feet) and the calibration statistics for the ADWR model demonstrate that the model does not have significant numerical error and was suitably calibrated as a regional groundwater assessment tool. Comparison of the simulated overall water budget values shows an increase of approximately 6,000 acre-feet per year (AFY) or an increase of approximately 25 percent relative to estimated 1941 groundwater conditions. The change in total water budget is attributable to an increase of approximately 8,000 AFY of estimated pumping between 1941 and 1990. This increase in basin groundwater demand was offset primarily by changes in groundwater storage, although simulated reductions in both surface water flows and ET along the major river corridors also contributed approximately 3,000 AFY to offset the additional pumping over this time period.

3.1.3 Summary – ADWR Model

The importation, simulation, and review of the ADWR Model provides valuable information regarding the spatial distribution of hydraulic parameters and primary water budget components. Additionally, the model provides insight as to the differences between water budget features within the Sierra Vista subwatershed and the regional conditions detailed in the more recent USGS Model. However, it was evident that the model would require significant updates and refinements for it to be used for the purposes of this study. This determination was based primarily upon the model discretization (cell size and number of layers), outdated parameterization, and the need for an extensive update to recalibrate the model to present-day groundwater pumping and water level observations.

Cell size in the ADWR Model is as large as half a mile, which would require refinement for a viable analysis of current and future effects of recharge from the Sierra Vista WRF. Vertical discretization of the regional hydrostratigraphy into three model layers is also coarser than what would be optimal for assessing the localized geologic layering and the presence of a hydrogeologically relevant clay unit located between the Sierra Vista WRF and the San Pedro River. The five-layer USGS Model, recently calibrated and released by the USGS, allows more flexibility in simulating both the physical presence of the local clay unit and its potential effects on the migration of WRF recharge. For these reasons, the bulk of this project's efforts have been focused upon importing, operating, and reviewing the construction and simulation results from the USGS model.

3.2 USGS Upper San Pedro Basin Groundwater Model

The USGS groundwater flow model for the Upper San Pedro Basin (USGS Model) was developed using MODFLOW-2000, an updated, finite-difference, MODFLOW groundwater modeling code (Harbaugh, 2000). GMS^{TM} version 5.0 was utilized by the USGS as the pre- and post-processor (Aquaveo, 2008). The USGS Model builds upon the previous modeling efforts within the basin although it expands both the spatial extent as well as the simulated time frame and has more refined vertical layering based upon regional lithology. The model was completed and published in 2007 and presently simulates transient groundwater conditions from 1902 through March 2003 (Pool and Dickinson, 2007). The USGS Model has been selected to be the foundation for the modeling activities detailed in the Scope of Work for the Sierra Vista WRF Groundwater Modeling Study.

3.2.1 USGS Flow Model Construction

As shown on Figure 3-2, the USGS Model domain covers the upper drainage basin of the San Pedro River, which includes portions of northern Sonora, Mexico and the Sierra Vista subwatershed in Arizona. Specifications for the USGS Model are detailed in Table 3-3. The active model domain covers an area of approximately 1,700 square miles, and extends from Cananea, Mexico, north to Fairbank, Arizona. The active area is bounded by the Mustang and Huachuca Mountains on the west and the Mule Mountains, Tombstone Hills, and Sierra San Jose on the east. The San Pedro River is represented by numerical stream cells in the USGS Model, as it flows north from its origination in the higher elevations in Sonora, Mexico, crosses the international boundary, and exits the active model domain approximately 50 miles from its source drainages. The USGS Model covers approximately three times the extent of the ADWR Model (500 square miles). This greater extent is significant in that the USGS model explicitly simulates more distal, natural hydrologic boundaries (both inflows and outflows) relative to the ADWR model.

Table 3-3. Specifications of the USGS Groundwater Model for the Upper San Pedro Basin

Model Characteristics	Specifications
Active Model Domain	~1,700 square miles, ~1,100,000 acres
Units	Time: Days Length: Meters (lateral and vertical)
Coordinate System	UTM NAD83, Zone 12N GIS: lateral units in meters, vertical units in meters
Model Grid	440 rows by 320 columns, 704,000 total cells, 115,531 active cells Origin X: 529,999.951 Y: 3,419,999.983 (No rotation)
Cell Size	250 meters by 250 meters (uniform) 820 feet x 820 feet 0.155 mile x 0.155 mile
Layering – 5 Layers	*Layer 1:* Pre and post-entrenchment stream alluvium, and the sand and gravel facies of the upper basin fill. LAYCON = 1 (Unconfined) *Layer 2:* Sand, gravel, silt and clay facies of the upper basin fill. LAYCON = 3 (Unconfined/Confined; T varies) *Layer 3:* Sand, gravel, siltstone, and mudstone facies of the lower basin fill. LAYCON = 3 (Unconfined/Confined; T Varies) *Layer 4:* Sand and gravel facies of the lower basin fill. LAYCON = 3 (Unconfined/Confined; T varies) *Layer 5:* sand and gravel facies on the perimeter of the alluvial basin of the lower basin fill; siltstone and conglomerate of the Pantano Formation, and consolidated rock. LAYCON = 3 (Unconfined/Confined; T varies)
Hydraulic Parameters	*Layer 1:* K = 5.0 m/d to 7.5 m/d; Sy = 0.2 to 0.3 ; SS = 0.000001 *Layer 2:* K = 0.02 to 5 m/d; Sy = 0.05 to 0.25 ; SS = 0.00002 *Layer 3:* K = 0.001 to 4 m/d; Sy = 0.05 to 0.1; SS = 0.000005 to 0.00001 *Layer 4:* K = 0.00025 to 12.5 m/d; Sy = 0.05 to 0.25; SS = 0.000005 *Layer 5:* K = 0.000125 to 1.25 m/d; Sy = 0.001 to 0.25; SS = 0.000001
MODFLOW Packages	MODFLOW 2000, Drain, Well, Stream, ET, Recharge, BAS, DIS, LPF
Simulation Time of USGS Model	1902-2003; Steady State calibration performed to match pre-1961 conditions (see section 3.2.8 for more details)
Stress Periods and Simulation Time of Final Transient Simulation	34 Seasonal Stress Periods, 10 time steps each, 1.5 multiplier Begins on March 12, 1986 and continues to March 11, 2003.
Recharge	Cell inputs range from 0.001 to 17.5 ft/yr
Wells	Imported as 4,699 prescribed flux analytical element wells (Note: These wells sum to a total pumping value for each model node. They include both pumping and recharge wells)
Boundary Conditions	Constant Heads at the North end of the model to represent underflow to the remaining portion of the Upper San Pedro Basin
Initial Conditions	Resulting heads from the immediately previous steady-state or transient model
Solution Method	Preconditioned-Conjugate Gradient 2 (PCG2)

3.2.2 Discretization and Layering

The USGS Model grid consists of 440 rows and 320 columns with a uniform grid cell spacing of 250 meters by 250 meters, or 0.024 square miles. The active model domain covers approximately 1,700 square miles, and is georeferenced within the Universal Transverse Mercator (UTM) Coordinate System, North American Datum (NAD) 1983, Zone 12 North. Both horizontal and vertical units are in meters.

The hydrostratigraphy of the USGS Model is divided into five nested layers of varying extents based upon subsurface lithologies (Figure 3-2). The top of the highest active layer at any location within the model represents ground surface. Elevations were interpolated from 60-meter Digital Elevation Models (DEM) for Mexico, and higher resolution 1-meter, 10-meter, and 30-meter DEMs for the United States. A brief lithologic description of each layer is provided above in Table 3-3.

Layers 1, 2, and 3 were not extended into Mexico by the USGS due to the lack of lithology and hydrogeologic information. According to Pool and Dickinson (2007), the base of Layer 5 was set uniformly at 1,500 meters below land surface. However, upon inspection of the digital model files, actual depths to the bottom of Layer 5 vary where Layer 4 is not present.

The USGS Model simulates stresses on the aquifer from 1902 through March 2003. Due to the fine discretization of the model grid and the large number of stress periods, output files are extremely large and model runs are resource-consuming. The model simulation was therefore separated into several linked transient models of approximately a decade each. These models were set up to use the output of the previous model as the input for the successive simulation. Additionally, the stress periods for the model are separated into seasonal time frames. The Spring/Summer season is simulated from March 12 to October 15 and the Winter/Fall season is simulated from Oct 16 to March 11. These time frames bracket the two prevailing periods of elevated precipitation discussed in Section 2.2.

For the purposes of this project the focus of this review is the final transient model simulation which simulates the period from March 12, 1986 to March 11, 2003.

3.2.3 Model Boundaries

No flow, or inactive, cells were assigned to the edges of the model representing the lateral extent of the groundwater basin. Due to the nested layering of this model, no flow cells were also defined along the edges of each model layer. The extent of each model layer can be viewed on Figure 3-2, and individually on Figures 3-3 through 3-7. Where an overlying layer does not exist within the active model domain (or terminates laterally), the immediately underlying layer can be assumed to be present at ground surface. The northern boundary also includes no flow conditions for a substantial portion of its length in order to force groundwater flow into a direction parallel to this boundary and toward the northern reaches of the San Pedro River (Figure 3-2). These groundwater flow conditions are consistent with observed gradients near the northernmost extent of the USGS Model.

Constant, prescribed head boundary condition cells were placed along the central portion of the northern boundary in Layers 4 and 5 (Figure 3-2). Constant head cells are located to the east of the San Pedro River in Layer 4, and to the west and east of the San Pedro River in Layer 5. The placement of these constant head locations coincide with areas where the groundwater flow gradients are directed out of the model domain at an acute angle, providing a source of underflow across the northern model boundary. Values for this boundary were based on interpretations of water-level monitoring data compiled by the USGS; however, the flux exiting the model from these boundary cells is conceptually reasonable from a hydrogeologic standpoint.

3.2.4 Aquifer Hydraulic Properties

Horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and specific yield were all estimated based on the extents of the interpreted basin lithology as well as spatial variations in hydraulic gradient. The USGS report is unclear if aquifer testing data was also explicitly included in the development of the hydraulic parameter distributions. All horizontal hydraulic conductivity values in the USGS Model are currently representative of isotropic conditions.

Figures 3-3 through 3-7 display the spatial distribution of horizontal hydraulic conductivity values for each model layer and allow the inspection of the calibrated distribution of hydraulic parameters and regional heterogeneity relative to major hydrologic and geographic features. Distributions of other major hydraulic parameters are provided in the database of electronic files (Appendix Z).

As seen on Figure 3-3, Layer 1 hydraulic conductivity values range from 5 meters per day (m/day) to 7.5 m/day and are uniformly higher than those assigned to underlying layers. The highest conductivity values in this layer correspond to the streambed alluvium associated with the current course of the San Pedro River. The isolated, northwestern portion of Layer 1 encompasses the current location of the Sierra Vista WRF as well as Murray Springs. Specific yield for Layer 1 ranges from 0.2 to 0.3, with the smaller value corresponding to a small area approximately 2.5 miles due east of the Sierra Vista WRF.

As seen on Figure 3-4, Layer 2 hydraulic conductivity values range from 0.02 to 5 m/day. Relatively low conductivity values are encountered immediately to the east of Murray Springs; however, higher conductivity values can be found to the west of this location and beneath the Sierra Vista WRF. Specific yield for this layer ranges from 0.05 to 0.25, with the highest values of specific yield occurring in the southern extent of the layer. Specific storage for this layer was set uniformly at a value of 2×10^{-5} m^{-1}.

As seen on Figure 3-5, Layer 3 hydraulic conductivity values range from 0.001 to 4 m/day, and are generally lower than those at corresponding locations in the overlying layers. Specific yield values for this layer were set at either 0.05 or 0.1, with the 0.05 value comprising the majority of the middle of the basin. Specific storage values were set at either 1×10^{-5} m^{-1} or 5×10^{-6} m^{-1} with the higher value occurring within a discrete zone near the border with Mexico.

As seen on Figure 3-6, Layer 4 hydraulic conductivity values exhibited the largest variation in magnitude, ranging from 0.00025 to 12.5 m/day. The large range in conductivity values is primarily due to the fact that Layer 4 is much more regionally extensive than overlying layers and includes localized areas of alluvium associated with surface water features. Specific yield ranges from 0.05 to 0.25 with the highest values occurring in the southern portion of the layer, in Mexico. Specific storage for the layer is set at a uniform value of 5×10^{-6} m^{-1}.

As seen on Figure 3-7, Layer 5 hydraulic conductivity values range from 0.000125 to 1.25 m/day, a range of four orders of magnitude. Specific yield ranges from 0.001 to 0.25. Specific storage for the layer is set at a uniform 1×10^{-6} m^{-1}.

In comparison with the ADWR Model, hydraulic conductivity values are generally lower in the USGS Model. This trend is partially due to the different conceptualizations of the aquifer system and the more refined vertical layering discretization in the USGS Model. Model Layer 1 for both models can be considered to be conceptually equivalent based upon representative lithology. Likewise, each model's bottom layer (Layer 3 for the ADWR Model and Layer 5 for the USGS model) can be considered to be similar in their conceptualization and construction. However Layer 2 in the ADWR Model generally corresponds to model Layers 2, 3, and 4 in the USGS model.

The hydraulic conductivity values for the stream alluvium, represented in each model's Layer 1, are approximately twice as high in the ADWR model as those used in the USGS model. ADWR's Layer 2 hydraulic conductivity values range from 0.03 m/day to 7.6 m/day, whereas the USGS model hydraulic conductivity values for Layers 2, 3, and 4 encompass a more expanded range, from 0.000125 m/day to 12.5 m/day. Maximum values in the bottom layers for the ADWR Model and the USGS Model are 6 m/day and 1.25 m/day, respectively.

In general, the magnitude and spatial distribution of hydraulic parameters in the USGS Model are deemed to be the most appropriate framework for the development of the Sierra Vista Model. Additionally, the parameter values used in the USGS Model are of appropriate ranges for the lithologies defined, and given the more refined layering and grid cell spacings, this model is also suitable for updating layering and hydraulic parameters near the Sierra Vista WRF.

3.2.5 Recharge and Evapotranspiration

Both natural and artificial recharge are included in the USGS Model. Most of the natural recharge occurs along mountain fronts from runoff collected within ephemeral channels. Other areas of natural recharge occur along the San Pedro and Babocomari Riviers, within the limestone of the mountains, and along mountain front alluvial deposits. Artificial recharge sources within the model include treated effluent near Sierra Vista, Naco, Bisbee, Fort Huachuca, and Tombstone, wastewater from septic systems, mine wastewater discharge, excess irrigation, and leakage from potable water systems. Recharge from some sources, such as return flows from agricultural activity, was applied to the model as a reduction in the magnitude of simulated irrigation pumping rather than explicit surficial recharge. Model cell recharge values for the 1986 to 2003 simulation range from 0.001 feet/year (ft/yr) to 17.5 ft/yr, with higher values occurring near Bisbee and at the Sierra Vista WRF. The total annual amount of recharge applied to the USGS Model in 2003 is presented in Section 4.1. Additional information regarding recharge from the various sources discussed above can be found in Pool and Dickinson (2007) or obtained by contacting the USGS.

Seasonal ET was simulated for the riparian areas of the San Pedro River and the Babocomari River. Vegetation types within these areas were mapped for various years and used by the USGS to assign spatial distribution of ET. The ET extinction depth, defined as the maximum depth at which the vegetation can draw water, was set at a constant value of 6 meters below land surface. Maximum model cell ET rates ranged from approximately 3.0 to 7.7 ft/yr; however, simulated cell ET rates are less than these values as they are dependent upon the depth to water for each cell. The overall volume of ET in the model in 2003 is presented in Section 4.1.

The maximum model cell values for recharge and ET are higher in the USGS Model than those in the ADWR model. This is primarily because the USGS Model has a finer grid and expressly simulates recharge facilities as well as mine wastewater recharge. In contrast, the ADWR Model only simulated mountain front recharge and groundwater underflow as basin inflows. Conceptualization of ET was also different between the models: the USGS Model based ET rates on vegetation extents and published ET rates for the respective vegetation types, whereas ADWR based ET on an estimate of the reduction of stream baseflow due to vegetation. The ADWR Model approach would likely result in lower values than those values calculated by riparian total use because it neglects other potential sources of stream inflow and does not specifically consider vegetation types and patterns.

3.2.6 Stream Package

The MODFLOW streamflow-routing package (Prudic, 1989) was used to simulate the San Pedro River, Babocomari River, the Rio Los Fresnos, and other tributaries associated with springs that could contribute to flow in the San Pedro River. The entire stream package was made up of 93 stream segments of varying numbers of individual reaches, or individual stream cells. Streambed elevations were assigned to the start and end of each segment based on digital elevation models, and streambed thickness was set to a constant 0.5 meter. According to the USGS model report stream stage was allowed to be calculated during the simulation using a form of the Manning's equation. This equation requires stream width, slope, and Manning's roughness coefficient as inputs. Stream width was varied from 1 to 3 meters in the USGS Model. Sinuosity of the stream was accounted for by considering the ratio of the stream cell length to the actual stream reach length represented within that cell. The Manning's roughness coefficient was set uniformly to 0.02 for all stream segments. Although stream stages were calculated in the original release of the USGS Model, this option was not active in the most recent update of the USGS Model released to Brown and Caldwell in December 2008. Thus, the most current version of the USGS Model uses the prescribed stream stages to calculate stream leakage and does not currently use inputs such as Manning's coefficient.

3.2.7 Wells

Pumping and recharge wells are simulated as 4,699 transient wells (using the "WELL" package within MODFLOW) throughout all five model layers. MODFLOW simulates these wells as flux cells with a net demand of all of the wells contained within that cell. If a well is screened across multiple layers, a single flux cell will be assigned per layer that the well penetrates. Assignment of pumping rates was determined by various methods. Where pumping rates were known or recorded for specific wells those values were assigned directly to those wells. Other rates of pumping and their distribution were based on available information including irrigated land coverages, domestic well locations, and unincorporated use areas. Mine water use in Mexico was distributed at the approximate locations of withdrawal wells. Pumping rates were applied seasonally by considering various factors including ET data, agricultural practices, and other variations in water deliveries. Total pumping rates simulated within the USGS Model in 2003 are presented in Section 4.1.

Additionally, the vertical distribution of well screen intervals was determined by both knowledge of actual well depths and the existence of model layers at those locations. This produced a complex methodology for spreading the pumping impacts for wells across the various model layers. Where Layers 1, 2, 3, and 4 do not exist, wells were placed in Layer 5. Wells were assigned to Layer 4 when the system was unconfined within that layer and sufficient hydraulic connection was evident between the upper and lower basin fill units. Where conditions were confined, or where the presence of silt and clay limit vertical connection between model layers, pumping was distributed among Layers 1, 2, 3, and 4 depending on saturated thickness and hydraulic conductivity. Domestic wells outside of the confined portions of the aquifer were assigned to Layer 2 exclusively.

Agricultural withdrawals between Highway 90 and Hereford were assumed to be screened within confined aquifer units and were assigned to Layer 4. Pre-1940 agricultural withdrawals were assigned to Layer 2, whereas agricultural wells near Palominas were assigned to Layer 4.

3.2.8 Model Calibration Approach

The USGS Model calibration involved a process of assessing model agreement with both the steady-state (pre-development) and historical transient groundwater and surface water conditions. Steady-state calibration involved adjusting hydraulic conductivity values and vertical anisotropy to match historical hydrographs, predevelopment water level altitudes, and an estimate of the steady-state annual water budget. Two levels of steady-state calibration were performed: 1) an annualized, steady-state calibration to refine estimates of hydraulic conductivity and vertical anisotropy and 2) an "oscillatory" steady-state calibration to refine seasonal pumping, ET, and recharge estimates. The annualized steady-state calibration process resulted in a mean absolute error of 9.0 meters for 77 of the pre-1961 target values and a mean absolute error of 7.5 meters for 29 of the pre-1950 target values. Given a simulated range in head values of over 300 meters, this level of calibration is acceptable at a regional level.

Transient conditions were simulated from 1902 to 2003 using the results from the preliminary annualized and oscillatory steady-state simulations as initial conditions. Water level hydrographs for wells located throughout the entire basin were used for calibration, as well as seasonal surface flow data at the Charleston and Palominas stream gages. Parameters used for transient calibration included storage properties and vertical hydraulic conductivity. Post-1990 calibration was emphasized as water-level trends and seasonal pumping information for this time frame are better documented and have an improved temporal and spatial resolution.

Transient model calibration focused on matching both the trends and magnitude of groundwater hydrographs. Hydrographs used for the Sierra Vista area include pre-1980 water level data from D(21-21)29cca and post-1980 data from D(22-22)06dac. Hydrograph data evaluated for this area also included the Lewis Springs Monitor wells 1 through 6. According to the USGS report, simulated water-level trends matched observed trends from 1995 to 2003 in the vicinity of Sierra Vista. In support of this, hydrographs for D(21-21)29cca and D(22-22)06dac show a numerically valid trend match with observed water levels, exhibiting approximately 8 meters and 4 meters of difference in magnitude, respectively. The USGS Model appears to adequately represent trends in water levels over time as observed in the vicinity of the WRF.

Streamflow calibration was also performed to improve agreement between simulated and observed flow conditions along the San Pedro River. Simulated summer baseflow near Charleston for the period between 1936 and 1940 was 5.7 cfs compared to an observed value of 3.7 cfs. For the same period and location, simulated winter baseflow was 10.9 cfs versus an observed value of 12.4 cfs. Starting in 1940, significant amounts of near-stream groundwater withdrawal began in the Palominas/Hereford area resulting in a decline in observed summer baseflow from approximately 3.6 cfs in the early 1940s, to 1.1 cfs by 2003. Observed winter baseflow also declined by approximately 7 cfs during this time; simulated winter baseflow decline for the same time period was approximately 7.6 cfs, closely matched observed conditions.

Simulated summer baseflow near Palominas for the time period between 1936 and 1940 was 3.3 cfs compared to an observed value of 0.7 cfs. For the same time period simulated winter baseflow was

4.9 cfs at the same location, which is similar to observed flows. Due to the increase in agricultural withdrawals in the Palominas/Hereford area, a decline in summer baseflow to zero flow occurred between 1940 and 1950; however, the model simulation of summer baseflow reduced flow to zero much more gradually, from 1940 to 1970. Observed winter baseflow declined by approximately 3.8 cfs from 1940 to 1950. Again, the model simulated a more gradual baseflow decline, taking until approximately the 1960s to show this level of flow reduction.

3.3 Significance of USGS Model Calibration

Pool and Dickinson (2007) concluded that model calibration results demonstrate that the model "approximates observed trends in water levels throughout most of the model area and streamflow at the Charleston streamflow-gaging station on the San Pedro River". Although limited information regarding water level target locations and model residuals was available, the model appears to adequately reflect regional groundwater conditions within the Upper San Pedro Basin. The USGS report presented an observed water level versus simulated water level scatter plot (Pool and Dickinson, 2007, Figure 10a), as well as an observed water level versus model residual for model calibration (Pool and Dickinson, 2007, Figure 10b). The observed versus simulated water level graph generally shows a one-to-one relationship between 1,150 and 1,440 meters amsl.

According to the USGS Model, simulated water levels at the Sierra Vista WRF location range from 1,260 to 1,275 and show good agreement with observed water levels. However, there is a slight bias toward simulating water levels 5 to 10 meters too high in the vicinity of the recharge basins (Pool and Dickinson, 2007, Figure 10a and 10b). Likewise, there appears to be good agreement with observed water levels near the elevation of Murray Springs and the San Pedro River immediately downgradient of the Sierra Vista WRF, further supporting the appropriateness of the use of the USGS Model for this project.

The ability of the USGS Model to adequately simulate changes in the observed flow at the Charleston stream gage, shown on Figure 1-1 and Figure 1-2, was also evaluated. Although the model currently overestimates the magnitude of summer baseflow and underestimates winter baseflow at this gage, it adequately simulates the historic decline in observed flow conditions for both seasons. Given the agreement between simulated and observed groundwater conditions in the vicinity of the Sierra Vista WRF, the USGS Model is deemed to be a suitable basis for the development of a tool to assess future changes in San Pedro River baseflows in response to localized recharge.

3.4 Limitations of the USGS Model

Pool and Dickinson (2007) document several limitations and possible improvements for the USGS Model, including:

- Improved outflow boundary conditions;
- Refined recharge and ET rates;
- Improved understanding of the location and magnitude of groundwater withdrawals within Mexico and in unincorporated areas in the U.S.;
- Improved knowledge of the vertical distribution of groundwater withdrawals within confined portions of the regional aquifer;

- Adjustment of model boundaries to address the potential of future changes in groundwater flow directions invalidating the location of no flow boundaries located within the regional aquifer system; and
- Improved stream package assumptions and/or use of an updated stream package to better determine the effects of recharge on the surface water flow system.

For the purposes of this study, the USGS Model's simplifying assumptions and associated limitations are acceptable as they do not significantly hinder the model's intended purpose of assessing interactions between regional groundwater and surface water conditions. Model hydraulic parameters; such as hydraulic conductivity, storage parameters and water budget components; are continually subject to refinement based upon the availability of new field data. However, the inclusion of recently available data within the vicinity of the WRF, is a part of this project.

Improvements to simulated streamflow estimates could be accomplished by implementing a newer and more comprehensive streamflow modeling package; however, this study is intended to evaluate relative changes to baseflow along the San Pedro River as a result of recharge from the Sierra Vista WRF. Given the fact that the existing USGS Model is capable of generally reproducing observed trends in San Pedro River baseflow declines, the current stream package developed by Prudic (1989) was deemed adequate for the purposes of the project.

Additional recommended model changes and clarifications were previously documented during the course of this project in *Technical Memorandum No. 1 - Review of Groundwater Flow Models Developed by the Arizona Department of Water Resources and United States Geological Survey for the Sierra Vista Subwatershed and Adjacent Portions of the Upper San Pedro Basin in Southeastern Arizona and Northern Sonora, Mexico* (Brown and Caldwell, 2009a).

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4. SUMMARY OF USGS MODEL IMPORT AND UPDATE

Brown and Caldwell successfully imported and performed simulations with the most current version of the USGS Model (released December, 2008). This section discusses the ability of the imported model to reproduce results documented by the USGS and provides details on (1) the revisions made to update the model, and (2) the calibration exercise performed to demonstrate the model's ability to simulate known conditions.

4.1 Importation and Simulation of USGS Model

The original, USGS Model MODFLOW-2000 dataset was obtained by Brown and Caldwell from the USGS and imported into Groundwater Vistas pre- and post processing software in December 2007. Observed discrepancies between model construction and documentation were identified and brought to the attention of the USGS in February 2008. All questions and discrepancies were addressed, and the final updated model dataset was provided to Brown and Caldwell in December 2008.

Once imported and verified, the model was run using all the original USGS inputs and parameters. Simulated water levels exhibit excellent agreement between output from the USGS and Brown and Caldwell versions of the model (Figure 4-1). Table 4-1 summarizes the final stress period water budget (March 2003) for the original USGS Model, Brown and Caldwell's import of it, and an import and simulation of the USGS Model performed by ADWR. All three model simulations are in very close agreement for all water budget constituents. Minor differences in individual components can be attributed to solver parameters and small numerical discrepancies. It should be noted that the budget comparison in Table 4-1 is for the winter season, which did not include evapotranspiration. During the stress period representing the 2002 summer season (stress period 33), evapotranspiration from the Brown and Caldwell import of the USGS Model totaled 13,527 AFY, which compares very closely to the USGS simulated value of 13,532 AFY.

Figure 4-2 presents a graph comparing storage and stream package water budget components from 1986 through 2003 for the USGS Model and the imported version of the model by Brown and Caldwell. Generally, both models exhibit very similar magnitudes and trends in these components over the simulated time period.

Based on the agreement between the simulated water budgets and water levels from the USGS and Brown and Caldwell imported model, the operation of the model was deemed successful. The imported USGS Model was then updated with key model stresses through 2008 and served as the basis for the creation of the Sierra Vista Model.

Table 4-1. Water Budget Comparison for USGS and Brown and Caldwell Simulations of USGS San Pedro Basin Model (AFY)

	USGS Model March 2003 (Stress Period 34)	Brown and Caldwell Import Model March 2003 (Stress Period 34)	ADWR Import Model March 2003 (Stress Period 34)
Inflows			
Recharge	19,112	19,112	19,112
Stream Leakage	5,719	5,648	6,319
Storage	31,638	31,906	31,836
Total	56,469	56,666	57,267
Outflows			
Constant Head	784	784	784
Pumping (Net)	28,219	28,219	28,219
Drains	438	438	438
Evapotranspiration*	0	0	0
Stream Leakage	11,453	11,370	12,048
Storage	15,625	15,846	16,170
Total	56,519	56,657	57,659

**Evapotranspiration was not active during the winter season represented by stress period 34.*

AFY = acre-feet per year

Note: The information contained in this table is based upon updated information obtained after release of project Technical Memorandum 1 (Brown and Caldwell, 2009a).

4.2 Model Update (2003-2008)

The import of the USGS Model by Brown and Caldwell was expanded to include stress periods representing March 2003 through October 2008. The additional stress periods are seasonal and consistent with the time frame of the original USGS Model build. Spatial distributions of evapotranspiration and recharge were held at the seasonal values applied at the end of the original USGS Model time periods with the exception of the groundwater recharge occurring at the Sierra Vista WRF. Reported recharge at the WRF infiltration basins as well as incidental recharge for the WRF treatment wetlands was applied as transient recharge cells from the onset of basin recharge operations at the WRF in 2002. Additional information regarding WRF recharge from the infiltration basins and wetlands is provided in Section 5.2.1.

Groundwater withdrawals for the following water providers were also updated in the model for March 2003 through October 2008:

- City of Sierra Vista
- Bella Vista Water Company
- Fort Huachuca
- PDS Water Company

- PDS Golf Course
- Arizona Water
- Cloud Nine Estates

Total groundwater demand for these providers was based on values provided by the City of Sierra Vista and documented in the 321 Reports to Congress. Pumping was assigned to individual wells and across appropriate model layers. The approach for the assignation of pumping rates in the model was identical to that used in the development of the Sierra Vista Model, described in Section 6.8. All other model construction details, layering, and hydraulic parameters were maintained as documented for the original USGS Model.

4.3 Spatial Calibration Statistics

A spatial calibration check was performed with the USGS Model to assess the regional agreement of simulated water levels with observed conditions. Measured water levels compiled over the course of this project from the USGS, ADWR, Bureau of Land Management (BLM), and City of Sierra Vista were imported into the updated USGS Model as calibration targets. The calibration statistics from running the model through October 2008 are presented below in Table 4-2. These statistics are based upon residual values, which represent the difference between simulated and observed water levels. Overall, the calibration of the temporally expanded and updated USGS Model meets a general calibration criteria of the residual standard deviation (or “root mean square error”) being less than 10% of the total range in observed head values for all three calibration periods (Table 4-2). Additionally, the absolute residual mean (ARM) is less than 5% of the total observed range in water levels for March 2003, and within 10% of the much more narrow range of water level targets in 2008. When considering the large range of water levels and steep gradients present within the model domain, these statistics demonstrate a high degree of calibration.

The statistically valid calibration of the updated USGS Model provides additional confidence in its use as the basis for developing a Sierra Vista Model capable of accurately simulating more localized groundwater conditions. The calibration exercise also supports the estimated and assumed values of groundwater pumping, WRF recharge, ET, and natural recharge for 2003 through 2008.

Table 4-2. Updated USGS Model Calibration Statistics

Date	Residual Mean (feet)	Residual Standard Deviation (RSD) (feet)	Absolute Residual Mean (ARM) (feet)	Observed Range in Target Values (feet)	ARM / Range	RSD / Range
March 2003	8.65	47.80	24.71	1,256.25	2.0%	3.8%
March 2008	3.87	23.21	18.06	267.8	6.7%	8.7%
October 2008	7.62	19.72	17.82	267.9	6.6%	7.4%

5. LOCAL-SCALE CONCEPTUAL MODEL

A local-scale conceptual model was developed to facilitate the simulation of recharge at the Sierra Vista WRF. Typically, regional-scale models are generalized at the local scale, and it was anticipated that refinements would need to be made to support the transition from the USGS Model to the Sierra Vista Model. The baseline data collection that began in 2002 supported the refinement of the layering and parameterization in the vicinity of the WRF. New data that was used for this refinement was derived from the installation and geophysical logging of new wells by the City and BLM as well as spring, streamflow and water level monitoring in the vicinity of the WRF.

5.1 Sources of Data

A summary of the new data available to support the local-scale conceptual model is provided in Table 5-1. Sources include: the City of Sierra Vista, the BLM, ADWR, and the USGS. Baseline information, where feasible, was collected beginning in 2002, prior to the start of recharge operations. The BLM wells were installed in 2006 and 2008 and do not have a sufficient history of water level measurements to provide baseline data. However, the information from these wells included geologists' logs, drill cuttings, and geophysical logs that were extremely useful for analyzing and identifying the local subsurface stratigraphy. These data were thoroughly reviewed to refine the local conceptualization of the system. Locations for many of these sites are shown on Figure 5-1.

Table 5-1. Summary of Data Available for the Local-Scale Conceptual Model

Location ID	Well Log	Water Level	Flow Measurement
Sierra Vista WRF-01	X	X	--
Sierra Vista WRF-02		X	--
Sierra Vista WRF-03		X	--
Sierra Vista WRF-04		X	--
Sierra Vista WRF-05*	X	X	--
Sierra Vista WRF-06	X	X	--
Sierra Vista BH-2	X	--	--
Sierra Vista BH-3	X	--	--
Sierra Vista BH-4	X	--	--
ADWR GWSI 313341110132101	--	X	--
ADWR GWSI 313425110115401	--	X	--
ADWR GWSI 313506110113301	--	X	--
ADWR GWSI 313421110121401 (USGS)	--	X	--
BLM Murray-Perched Well	--	X	--
BLM Murray-Shallow Well	--	X	--
BLM Murray- Intermediate	--	X	--

Table 5-1. Summary of Data Available for the Local-Scale Conceptual Model

Location ID	Well Log	Water Level	Flow Measurement
BLM Murray-Deep Well**	X	X	--
BLM Murray Springs	--	--	Spring
BLM Horse Thief	--	--	Spring
BLM Moson Falls	--	--	Spring
BLM Lewis Springs	--	--	Spring
BLM-H1	X	--	--
BLM-H2	X	--	--
BLM-G	X	--	--
BLM-B	X	--	--
BLM-C	X	--	--
USGS Palominas Gage	--	--	Stream
USGS Charleston Gage	--	--	Stream
USGS Tombstone Gage	--	--	Stream

**Soil boring BH-2 log used for this location*

***Geophysical log, geologist's log and cuttings available and reviewed*

5.2 Local Groundwater Sources and Sinks

Local sources and sinks that are significant for the local-scale conceptualization include recharge via the treatment wetlands and rapid infiltration basins at the WRF, streamflow at the Charleston gage on the San Pedro River, and spring flows in nearby drainages, including Murray Springs. Groundwater pumping west of the WRF, in the vicinity of Fort Huachuca and Sierra Vista, has also produced a cone of depression that affects local groundwater flow gradients near the recharge site. A description of the preliminary conceptual water budget was previously documented during the course of this project in the *Technical Memorandum No. 2 Sierra Vista Hydrogeologic Conceptual* Model Development and Proposed Modeling Approach (Brown and Caldwell, 2009b). However, during development of the Sierra Vista Model the preliminary values reported in *Technical Memorandum No. 2* were refined during the calibration process and are presented as components of the results from the Sierra Vista Model simulations in Sections 7.0 and 8.0 as well as included in the digital model files in Appendix Z.

5.2.1 Artificial Recharge from the City of Sierra Vista

On average, approximately 1,950 AFY of reclaimed water has been recharged in the rapid infiltration basins at the Sierra Vista WRF since operations began in 2002 (Table 5-2). The annual volumes have decreased slightly over the last two years, which correlates with a recent drop in per capita water usage. Between 2007 and 2008, per capita usage fell 4 percent, to 138 gallons per capita per day. Recent upgrades by the City to monitor flows between the wetlands and infiltration basins have provided an estimate of total water consumption from the wetlands portion of the treatment process at the WRF. ET for constructed wetlands containing cattails and reeds was estimated using information from the National Engineering Handbook, issued by the U.S. Department of Agriculture (USDA) and the National Resources Conservation Service (NRCS) (2002). Monthly rates of incidental recharge were estimated by comparing the recorded influent and effluent rates for the wetlands with the acreage of active wetlands, recorded precipitation, recorded pan evaporation, and assumed evapotranspiration rates for a constructed wetlands containing primarily cattails and reeds. The average volume of incidental recharge was estimated to be 800 AFY (Table 5-2), which accounts for approximately 30 percent of wetlands influent. This value is significantly greater than assumed annual losses due to evapotranspiration.

Table 5-2. Recharge at the Sierra Vista WRF 2002-2008

Year	Volume of Recharge via Rapid Infiltration Basins (Acre-Feet)	Volume of Incidental Recharge from Wetlands (Acre-Feet per Year)
2002	926*	~800 AFY
2003	1,766	
2004	1,868	
2005	1,944	
2006	2,231	
2007	1,976	
2008	1,881	
TOTAL	12,592	5,600

**Partial Year*

5.2.2 San Pedro River Streamflow

A graph depicting the moving 30-day median streamflow versus average daily precipitation at the Charleston gage from 2000 through 2008 is provided as Figure 5-2. The location of the gage with respect to the Sierra Vista WRF is shown on Figure 5-1. Flows at the gage are highly variable and reflect a strong correlation to runoff from storm events. Yearly peaks occur during the July/August monsoon season, with a secondary peak of longer duration during the spring. The long-term winter baseflow at this gage has been estimated to be 10.9 cfs (Pool and Coes, 1999). For perspective, this can be compared to the total average volume of recharge from the Sierra Vista WRF recharge basins, calculated to be approximately 2.7 cfs. Observed changes to baseflow attributable to recharge at the WRF is difficult to separate from the impact of the runoff during the wet seasons as well as from climatic or other longer term hydrologic changes.

5.2.3 Spring Flow

Spring flows measured by the BLM at five springs in the vicinity of the WRF are presented on Figure 5-3. Spring flows in 2003 and 2004 were assumed to be representative of baseline conditions prior to recharge operations at the WRF. In all cases, baseline spring flow was lower than 0.2 cfs. Beginning in 2006, a clear increase in flow is reflected at Murray Springs (Figure 5-3), which is measured at a point located approximately 1.5 miles from the rapid infiltration basins (Figure 5-1). This magnitude of increase is not seen at the four other springs, and, at this time, the slight variations and increases in flow apparent at a few of the springs could still be attributed to natural variations, other water sources, reductions in other groundwater outflows, or standard measurement errors.

Unlike streamflow at the San Pedro, Murray Springs flow does not exhibit a direct correlation with the summer monsoons. On the contrary, spring flow at the site drops significantly during the July/August period. Because this decrease in flow does not correlate to recharge patterns at the WRF, other factors such as evapotranspiration or runoff and recharge from winter precipitation may be affecting observed flow patterns. Although the seasonal trends are persistent, an increasing trend in overall flow is readily apparent.

Figure 5-4 shows flow at Murray Springs for key time periods: March, June, October and December, as well as summer and winter seasons. Increases in March and December flows are the most significant; however, an increasing trend in flow is reflected for all months. When the measurements are combined into summer versus winter, as shown on the lower chart, the pattern of rise is more discernable. The slope of the rise in flow for summer and winter is similar, suggesting that the source of the increased flow is the relatively constant-rate recharge from the WRF, as opposed to seasonal influences such as precipitation or evapotranspiration. Using 2003 and 2004 as a baseline, the increase in winter flow is calculated to be 0.28 cfs (203 AFY) or approximatey 10 percent of the total average recharge at the WRF. The increase in summer flow is calculated to be 0.21 cfs (155 AFY). Thus, based on spring flow measurements, recharge activities at the WRF are apparently inducing an increase in baseflow in the drainage containing Murray Springs comparable to approximately 8 to 10 percent of average annual recharge at the WRF. If incidental recharge from the WRF wetlands is also considered, these percentages decrease. Furthermore, losing reaches downstream of Murray Springs can infiltrate significant quantities of streamflow back into the local groundwater system prior to reaching the San Pedro River.

5.2.4 USGS Model Simulation of Streamflow and Spring Flow

A comparison of the USGS Model-simulated versus measured streamflow and spring flow for the local area is provided in Table 5-3. Because the model location for Murray Springs flow is located downstream and slightly north of the actual measurement location, the modeled spring flow is not directly comparable to the measured value. Given this difference, the model-simulated flow compares fairly well to the magnitude of spring flow measurements.

San Pedro streamflow at the Charleston gage includes a component from runoff, which is not reflected in the model-simulated estimates of baseflow. A direct comparison at a single point in time, therefore, has limited usefulness. However, a comparison of model baseflow to the median winter flow at the gage, shown in Table 5-3, demonstrates that the model-simulated streamflow is in good agreement with actual gage measurements. The Tombstone gage was considered to be too far downstream for the local conceptual area; therefore, it is not included in Table 5-3.

Table 5-3. Comparison of Model-Simulated Baseflow with Observed Streamflow and Spring Flow Measurements

Location	Observed Streamflow Measurements Winter 2003	Model-Simulated Baseflow March 2003	Observed minus Simulated
Murray Springs Flow	0.07 cfs	0.5 cfs	-0.43 cfs
San Pedro Streamflow (Charleston Gage)	5.8 cfs	4.5 cfs	-1.3 cfs

cfs = cubic feet per second

5.3 Groundwater Elevations and Gradients

Baseline water level measurements at the six WRF monitoring wells (see inset map, Figure 1-2) began in 2002, prior to the initiation of recharge operations. In addition, data from the ADWR Groundwater Site Inventory database (GWSI) were obtained and reviewed for relevance to potential responses from recharge at the Sierra Vista WRF. Water level hydrographs for both the City and relevant GWSI wells are presented on Figure 5-5. The data posted on Figure 5-5 represents the recent period of record available for data from each of these wells. (Note: the City reports that the sudden offset in measured water levels in early 2006 is due to non-correction of the removal of a section of line from a water level indicator device.)

WRF-02 and WRF-06 are located within the footprint of the rapid infiltration basins, thus they exhibit the largest water level rise and reflect variations from shifting water around the recharge basins to allow for drying cycles. Total rise to date is approximately 30 feet in WRF-02 and 43 feet in WRF-06. The response to recharge in these wells was almost immediate, versus the slight delays in response seen at WRF-01 and WRF-03, which are located approximately ¼ mile away from the basins, to the south and northwest, respectively.

As anticipated, WRF-04 and WRF-05 experienced the longest delay in response to recharge operations, as they are both the most distal and deepest wells in the monitoring network (Figure 5-5). Minor increases in the hydrographs are seen after about a year of operation, and more definitive rises are observed beginning in the summer of 2004. Other stresses such as groundwater pumping to the west may also be influencing the water level trends for these two wells.

From a review of the water level trends compiled in ADWR’s GWSI database, shown on Figure 5-5, it is apparent that some neighboring wells also experience a rise in water levels likely due to recharge at the Sierra Vista WRF. The locations of these wells and their distances from the WRF recharge basins are shown on Figure 5-1. In particular, GWSI wells “313425110115401” and “313421110121401” both exhibit a rise in water level over the time period in which water was being recharged at the WRF. Although the level of rise is somewhat muted relative to the WRF monitoring wells, these wells are located further away from the recharge basins. Likewise, GWSI wells “313341110132101” and “313506110113301”, located an even greater distance away from the WRF, both exhibit a negligible change in water levels given the quantity and quality of available water level data. This further reinforces the concept that, to date, appreciable rises in groundwater elevations associated with WRF recharge are limited to approximately one mile of the WRF site boundaries. Water levels at the GWSI well closest to the cone of depression (GWSI well 313341110132101) exhibits a slight decline over the period of record from 1997 through 2009. These nearby trends in groundwater elevations match the trends observed in simulations performed with the Sierra Vista model, where water level rises are limited to the immediate vicinity of the recharge basins and constructed wetlands, as well as areas immediately north and south of the WRF. Both observed and simulated water level rises are negligible west of the WRF, adjacent to the historic groundwater cone of depression. However, it should be noted that these hydrographs do not show how much additional drawdown might have been offset by WRF recharge. Future estimates of the full beneficial impact of recharge at the Sierra Vista WRF are presented in Section 8.0.

A total of four BLM monitoring wells were installed in 2006 adjacent to the drainage containing Murray Springs. They are located approximately 0.6 miles northeast of the rapid infiltration basins (Figures 1-2 and 5-1). Total depths range from 23 feet to 454 feet, and they are identified in order of increasing depth as perched, shallow, intermediate and deep. Note that these wells are approximately 1 mile upstream of the spring/streamflow measurement location for Murray Springs and also upstream of the first occurrence of seeps and springs, as recorded from field reconnaissance by Brown and Caldwell, June 25, 2009. Hydrographs for the BLM Murray Springs monitoring wells are shown on Figure 5-6. Water level data in this area prior to recharge activities at the WRF are not available; however, it can be assumed that the impacts of recharge would have begun in 2006 or earlier, based on the trends observed at both the spring discharge and spring flow measurement location.

Since 2006, approximately ½ to 1 foot of response is reflected in the perched (MUR-PER) and shallow (MUR-SH) monitoring wells. There is a strong downward gradient seen from the water levels in the BLM wells at this location, with approximately a 100-foot head difference between the perched and the deep wells. This gradient implies that groundwater recharge is fully impacting the most shallow aquifer units but may not presently be fully offsetting either groundwater pumping demands or pressure differences in the lower aquifer units penetrated by the deeper BLM wells. This is likely caused by fine-grained units limiting the immediate downward migration of recharged water between the various aquifer units accessed by the screened intervals of the BLM wells. However, this vertical gradient does not mean that the recharged water has not or will not eventually reach deeper aquifer units, only that it is more likely to flow laterally in the vicinity of the WRF and seep into deeper units over a larger areal extent associated with greater radial distances from the recharge basins and constructed wetlands. No discernable impacts from recharge at the WRF have been seen in the intermediate and deep well hydrographs since 2006. Furthermore, although one of the wells is labeled “perched” there has yet been no definitive evidence of perched conditions at this location based upon water level measurements. Additional information on well construction for all the BLM Murray wells is required to learn more about the nature of the local aquifer units, and additional lithologic and geophysical data collected between or adjacent to the WRF and Murray Springs would greatly benefit the spatial correlation of fine grained units.

Five additional BLM wells were installed in early 2009, and the locations of the wells closest to the WRF are show on Figure 5-1. Of the five wells, only BLM-B and BLM-C are close enough to be useful in the refinement of the local geologic conditions for the conceptual model.

The USGS Model-simulated water levels were compared to baseline water levels for the wells shown in Table 5-4. These wells were selected as being the most representative of water levels seen in Layers 1 and 2 of the model. For wells installed more recently, the current water level was compared to the model-simulated water level in 2003 as a first approximation of the differences that could be expected when the model is updated through 2008. Good agreement is seen between the simulated and measured water levels for most well locations, and the variations are consistent with what could be expected in a calibrated, regional-scale model.

Table 5-4. Comparison of USGS Model-Simulated versus Observed Local Water Levels in the Vicinity of the WRF

Well	Ground Surface Elevation (ft amsl)	Observed Baseline Water Level (April 2002)	Current Water Level (December 2008)	Model-Simulated Water Level (March 2002)	Water Level Difference (feet)
WRF-01	4264	4,195	4,205	4,173	-22
WRF-02	4247	4,183	4,212	4,168	-15
WRF-03	4253	4,179	4,199	4,168	-11
WRF-04	4283	4,166	4,168	4,172	6
WRF-05	4311	4,169	4,165	4,175	6
WRF-06	4246	4,176	4,217	4,168	-8
MUR-PER	4188	-	4,176	4,163 (Layer 1)	-13
MUR-SH	4188	-	4,161	4,163 (Layer 1)	2
BLM-B*	4322	-	4,184	4,181	-3
BLM-C*	4223	-	4,133	4,114	-19

Highlighted cells represent the values used to calculate the water level difference.

**Ground Elevation was taken from a USGS Digital Elevation model*

5.4 Thick Silt and Clay Intervals

The USGS identified a regionally extensive, thick silt and clay interval in the basin fill of the Upper San Pedro Basin. It is largely coincident with the current course of the San Pedro River, but trends west of the river in the vicinity of the WRF (Pool and Dickinson, 2006). The WRF site straddles the western boundary of this fine-grained interval (Figure 5-7), and the presence of these fines near ground surface is considered to be one of the mechanisms that produces some of the springs east of the WRF. Given this fact, the presence, thickness and hydraulic parameters of shallow fine grained materials are important in the local conceptualization. Well logs for monitoring wells and boreholes at the WRF and for the BLM monitoring wells provide additional subsurface, lithologic information that was not available at the time the USGS Model was developed. Local refinement of the silt/clay layers in the USGS Model was performed based on these new data points and is described further in Section 6.5.

Specifically, the new data were reviewed with respect to the elevation of the upper contact of the fine-grained intervals, represented by Layers 2 and 3 of the USGS Model (Figure 5-7). Geologists' logs from the WRF included two for existing monitoring wells (WRF-01 and WRF-02) as well as soil boring logs (BH-2, BH-3, BH-4) from drilling in 1997 (Fluid Solutions, 2002). A suite of geophysical logs were run on the BLM's deep well located at Murray Springs, and on their regional wells, including BLM-B and BLM-C. Cuttings from the drilling of the shallow and deep BLM Murray wells were also made available and have been inspected by Brown and Caldwell staff. Clay was observed in cuttings collected from throughout the borehole(s); however, the geophysical logs for the deep well suggest that, although fine-grained, the subsurface lithology was not pure clay and would transmit water. Thus, a conclusive assessment of the location and local correlation of potential "perching" clay units was not possible with the available data. No revisions to model layering were made based on lithologic information from the cuttings; however, the fine-grained nature of the subsurface was accounted for in adjustments to hydraulic conductivity (Section 7.1). Future model refinements and revisions should include additional lithologic data collection and interpretation for all available well logs in the vicinity of the WRF. Although the scale of both the USGS Model and Sierra Vista Model is regional, future local-scale modeling in the vicinity of the WRF, cone of depression, and San Pedro River would benefit from new or previously unutilized lithologic data that would aid in the refinement of existing model layer elevations as well as the generation of additional model layers for aquifer sub-units.

All logs were inspected for the presence of fine-grained intervals and hydraulically tight clay units. On resistivity logs, the tight clays were defined as intervals measuring less than or equal to 10 ohm-m. After the presence of any tight clays was identified, the vertical intervals above and below were inspected to determine if the clay signaled the presence of a thicker package of fine-grained material. The majority of the wells did not extend beyond the bottom of Layer 3 of the model (i.e., the vertical extent of the silt/clay interval), thus refinements of Sierra Vista Model layering were limited to the top of the silt/clay, or the bottom of Layer 1 in the model.

Table 5-5 compares the elevation of the top of the silt/clay interval from various logs with the corresponding top of the fine-grained interval in the USGS Model. The silt/clay interval needs to be thickened (the bottom of Layer 1 raised) at three of the four locations, and lowered slightly at the Murray deep well location. Figure 5-8 presents a conceptual cross section for the shallow subsurface materials in the vicinity of the WRF. It demonstrates how the current layering from the USGS Model should be adjusted to reflect the lithologic data collected at WRF-01 and the BLM Murray Springs wells. Also shown in Figure 5-8 are water level elevations for select monitoring wells in 2002 and 2008 along with the simulated water table from the model for 2003. The offset between the 2002 and 2008 water levels illustrates the impact of recharge at the WRF site, whereas the offset between observed and simulated conditions in 2002 and 2003, respectively, illustrates the underestimation of water levels by the original USGS Model.

Given the basin scale of the USGS Model and the scarcity of data points available near the WRF at the time it was developed, the differences presented in Table 5-5 and shown on Figure 5-8 are not substantial when compared to the overall thickness of the layers being adjusted. By comparing the conceptual cross section presented on Figure 5-8 with the larger scale cross section derived from the model layering on Figure 5-7, it was determined that layer adjustments of this magnitude would not significantly impact regional groundwater conditions and conceptualizations.

Table 5-5. Comparison of the Elevation of Fine-Grained Intervals in the USGS Model versus Logs from New Wells

Well	Silt/Clay Elevation	USGS Model Layer 1 Bottom Elevation	Elevation Difference (feet)
WRF-01	4,150	4,107	43
WRF-02	*4,070*	4,008	62
WRF-03	-	4,064	-
WRF-04	-	*	-
WRF-05	4,148	*	-
WRF-06	*4,070*	4,008	62
MUR-DP	3,937**	3,959	-22
BLM-B	4,158	*	-
BLM-C	4,133	*	-

**Layer 1 does not exist at this location*

***Based upon surveyed well elevation provided by City of Sierra Vista*

Note: All elevations in feet above mean sea level.

Italicized values are interpolated.

Wells BLM-B and BLM-C are located in regions where Layer 1 is not present. BLM-C is located in a region identified by the USGS as being dominated by a thick silt/clay interval, whereas BLM-B is located outside of this area. Geophysical logs for these two wells support this differentiation, as BLM-C is largely fine-grained with only minor coarser intervals to its total depth of just over 500 feet. Represented by Layer 2 of the model, the local model hydraulic conductivity for this region is estimated to be 0.16 ft/day, a value consistent with the fine-grained nature of the interval. BLM-B penetrates slightly coarser materials, with sandy lenses typically less than 10 to 20 feet thick. The USGS Model hydraulic conductivity of 3.3 ft/day for this area also seems appropriate given the local lithologic observations. No refinements were recommended for these two locations of the Sierra Vista Model.

6. SIERRA VISTA MODEL DEVELOPMENT

The Sierra Vista Model was used to simulate the future impacts of recharge at the WRF on both groundwater and surface water conditions within the Sierra Vista Subwatershed. This section provides information regarding basic construction and development of the Sierra Vista Model as well as descriptions of its refinements, modifications, and differences from the original USGS Model.

6.1 Approach

The Sierra Vista Model is based heavily upon the USGS Model construction and calibration. Both models have the same model origin, and model cell spacing. Refinements to the USGS Model construction completed during the development of the Sierra Vista Model included:

- "cropping" the original USGS Model domain just south of the U.S. – Mexico International Border (Figure 6-1),
- refining Layer 1 bottom elevations in the vicinity of the WRF,
- extending the model timeframe and stress periods to October 2008 (as previously done with the updated USGS Model),
- updating groundwater demands and artificial recharge where suitable information is readily available, and
- recalibrating the model to ensure acceptable water level agreements and simulated water budgets.

Specifications for this model are detailed in Table 6-1. Some differences in hydraulic parameters between the USGS and Sierra Vista Models are due to the removal of the Mexico extent of the USGS Model and its associated parameter values as well as parameter updates applied during model calibration and refinement.

Table 6-1. Specifications of the Sierra Vista Groundwater Model

Model Characteristics	Specifications
Active Model Domain	~1,135 square miles, ~725,000 acres
Units	Time: Days Length: Meters (lateral and vertical)
Coordinate System	UTM NAD83, Zone 12N GIS: lateral units in meters, vertical units in meters
Model Grid	440 rows by 320 columns, 704,000 total cells, 81,160 active cells Origin X: 529,999.951 Y: 3,419,999.983 (No rotation)
Cell Size	250 meters by 250 meters (uniform) 820 feet x 820 feet 0.155 mile x 0.155 mile
Layering – 5 Layers	*Layer 1:* Pre and post-entrenchment stream alluvium, and the sand and gravel facies of the upper basin fill. LAYCON = 1 (Unconfined)

Table 6-1. Specifications of the Sierra Vista Groundwater Model

Model Characteristics	Specifications
	Layer 2: Sand, gravel, silt and clay facies of the upper basin fill. LAYCON = 3 (Unconfined/Confined; T varies) *Layer 3:* Sand, gravel, siltstone, and mudstone facies of the lower basin fill. LAYCON = 3 (Unconfined/Confined; T Varies) *Layer 4:* Sand and gravel facies of the lower basin fill. LAYCON = 3 (Unconfined/Confined; T varies) *Layer 5:* sand and gravel facies on the perimeter of the alluvial basin of the lower basin fill; siltstone and conglomerate of the Pantano Formation, and consolidated rock. LAYCON = 3 (Unconfined/Confined; T varies)
Hydraulic Parameters	*Layer 1:* K = 4.0 m/d to 7.5 m/d; Sy = 0.3 ; SS = 0.000001 *Layer 2:* K = 0.02 to 5 m/d; Sy = 0.05 to 0.25 ; SS = 0.00002 *Layer 3:* K = 0.001 to 4 m/d; Sy = 0.05 to 0.1; SS = 0.000005 to 0.00001 *Layer 4:* K = 0.001 to 6.25 m/d; Sy = 0.05 to 0.25; SS = 0.000005 *Layer 5:* K = 0.000125 to 0.625 m/d; Sy = 0.001 to 0.2; SS = 0.000001
MODFLOW Packages	MODFLOW 2000, Drain, Well, Stream, ET, Recharge, BAS, DIS, LPF, CHD
Stress Periods and Simulation Time	Base Model: 45 Seasonal Stress Periods, 10 time steps each, 1.5 multiplier Begins on March 12, 1986 and continues to October 15, 2008. Predictive Model: 65 Seasonal Stress Periods, 10 time steps each, 1.5 multiplier Begins on October 16, 2008 and continues until March 11, 2041.
Recharge	Cell inputs range from 0.001 ft/yr to 28.5 ft/yr
Wells	Imported as 4,586 prescribed flux analytical element wells. (Note: These wells sum to a total pumping value for each model node. They include both pumping and recharge wells.)
Boundary Conditions	Constant Heads at the North end of the model to represent underflow to the remaining portion of the Upper San Pedro Basin; Constant Heads along the Mexican Boundary to represent underflow from the Mexico portion of the Basin
Initial Conditions	Resulting heads from the immediately previous transient USGS model
Solution Methods	Geometric Multi-Grid (GMG)

6.2 Computer Code Description

As with the USGS Model, the Sierra Vista Model is fully compatible with MODFLOW-2000 (Harbaugh, 2000). Groundwater Vistas™ was utilized as the pre- and post-processing software, coupled with ESRI® ArcGIS™ and associated standard GIS format datasets (ESI, 2006; ESRI, 2006).

6.3 Units and Coordinate System

The Sierra Vista Model uses the same units and coordinate system as the USGS Model: linear units of meters, temporal units of days, and all model features georeferenced within the UTM NAD83, Zone 12N projection and using the North American Vertical Datum 1988 (NAVD88). GIS files provided in Appendix Z are also all georeferenced in this coordinate system.

6.4 Model Domain and Southern Boundary

As shown on Figure 6-1, the full active model domain of the Sierra Vista Model coincides with that of the USGS Model in terms of the number of rows and columns as well as model origin, with the exception that it does not consider the portion of the basin that extends into Mexico. The removal of the southernmost section of the model entailed cropping the extents of Layers 4 and 5 along a transect located approximately one mile south of the U.S. – Mexico International Border. The one mile buffer applied to the southern model boundary was used to allow the inclusion of the full extents of model Layers 2 and 3 in the Sierra Vista Model.

Prescribed head boundary conditions were added to the Sierra Vista Model along its southern boundary near the U.S. – Mexico International Border in Layers 4 and 5. Layers 1 through 3 terminate north of this boundary; therefore, no additional boundary conditions were required for these layers. Prescribed head values were assigned in the Sierra Vista Model based on simulated head values in the corresponding cells of the original USGS Model for each model stress period. Due to the large distance between the WRF and the boundary (15 miles), unwanted influences from the constant head boundary in the vicinity of the WRF were not expected. However, groundwater fluxes and gradients were monitored along and adjacent to this boundary during all transient simulations to verify this assumption.

Prior to adjusting layering, pumpage, recharge, and hydraulic parameters within the Sierra Vista Model, water levels from this model version were compared to USGS Model water levels to ensure that the new boundary conditions did not unduly influence the regional flow regime. Figure 6-1 shows the excellent match to the USGS Model March 2003 water levels achieved with the Sierra Vista Model.

6.5 Model Discretization and Layering

The USGS Model cell discretization of 250 meters by 250 meters (or 0.155 mile by 0.155 mile) was found to be sufficient resolution for the purposes of this modeling application and the Scope of Work for this project. Similarly, the 5-layer approach used by the USGS was deemed to be appropriate for the purposes of the proposed recharge simulations and also remains largely unchanged. However, as discussed in Section 5.4 refinements to the bottom of Layer 1 were necessary for a localized area in the vicinity of the Sierra Vista WRF where recent lithologic information was available.

To incorporate these changes into the Sierra Vista Model, the original bottom elevation values for Layer 1 were extracted. Where new data exists in the vicinity of the WRF, the original Layer 1 bottom elevations were deleted within a 0.5 mile buffer around each new data point. The estimated elevation values interpreted from the recent lithologic data were then added to the full model data set and interpolated, or “kriged” along with the remaining Layer 1 bottom elevations at a resolution appropriate to the model cell spacing. The newly interpolated elevations were then used to replace the original Layer 1 bottom elevations. This method ensured that all available and suitable data points would be incorporated into the model and used to influence surrounding cells during interpolation. It resulted in a bottom of model Layer 1 that smoothly integrates recent lithologic information regarding the thick silt and clay intervals with regional interpretations previously developed and reviewed by the USGS.

6.6 Stress Periods and Initial Conditions

The original USGS Model simulates stresses on the aquifer from 1902 through March 2003. The model simulation was separated into several linked transient models of approximately a decade each. These models were set up to use the output of the previous model as the starting heads for the successive simulation. This Scope of Work focused solely on the final transient model, which simulates the period from March 12, 1986 through March 11, 2003.

The time frame for the Sierra Vista Model simulates conditions from March 1986 through October 2008. This extension of five and a half years, relative to the original USGS Model, was represented by 11 additional, seasonal stress periods. The duration and seasonality of the stress periods is consistent with the original model build.

Initial conditions, or heads, for the Sierra Vista Model rely on output from the final stress period of the previous transient model in the original USGS series; these heads were imported directly from the original dataset provided by the USGS in December of 2008.

6.7 Hydraulic Parameterization

Hydraulic parameters in the Sierra Vista Model remain unchanged from the original USGS Model with the exception of localized zones in the vicinity of the WRF. The revisions made to these zones during refinement and calibration process are discussed in Section 7.1.

6.8 Sources and Sinks

The Sierra Vista Model includes updates to pumping and recharge for 2003 through 2008 as previously summarized in Section 4.0. This was based upon data for the infiltration basin recharge provided by the City, annual reported groundwater withdrawals, as well as an estimate of average annual incidental recharge for the treatment wetlands.

Groundwater withdrawals for the following water providers were updated in the model for March 2003 through October 2008:

- City of Sierra Vista
- Bella Vista Water Company
- Fort Huachuca
- PDS Water Company
- PDS Golf Course
- Arizona Water
- Cloud Nine Estates

Total groundwater demands for these providers were based on values provided by the City of Sierra Vista and documented in the 321 Reports to Congress. Pumping was assigned to individual wells and model layers in the following manner. For each entity listed above, the fraction of total pumping attributable to each well was calculated for the last two seasons in the original USGS model (2002-2003). The fraction of pumping occurring in each model layer was also determined for each well. Total reported pumping amounts for each entity from March 2003 through 2008 were then multiplied by both fractions for each model cell to produce a distribution of pumping rates similar to the original USGS Model. During the update, it was noted that pumping for the City of Sierra Vista wells was not reflected after 1996. Reported pumping values for the City's wells were added to the Sierra Vista Model from 1997 through October 2008. Based upon new information, pumping for retired agriculture near Palominas was also discontinued in the model after 2003 (Don Pool, USGS, personal communication 2008). All other pumping in the model was maintained through October 2008 at the seasonal rates applied to the USGS Model in 2002-2003.

Seasonal ET was held at its 2002-2003 rates, extinction depths, and spatial coverage for 2003 to 2008. Recharge at the WRF facility was simulated at reported volumes from 2002 through 2008 as provided by the City for the infiltration basins (Table 5-2). Also included was an estimated 800 AFY of incidental recharge from the treatment wetlands. Additional details regarding this incidental recharge are provided in Section 5.2.1. Recharge cells were used to simulate all seasonal recharge at the 2002-2003 rates with the exception of recharge associated with the WRF, which was allocated over the full footprint of both the basins and wetlands (Figure 1-2 and Figure 5-1).

6.9 Groundwater/Surface Water Interaction

The stream package construction used in the original USGS Model was left largely unchanged in the Sierra Vista Model. The option for stream stage to be calculated by the model was left inactive. This causes the model to use the prescribed stream heads defined for each stream reach and is an approach consistent with the USGS Model build.

As mentioned in Section 3.2.6, the simulated location of Murray Springs in the USGS Model is several model cells downstream of its currently documented location. To address this issue the stream package was augmented by adding 5 additional stream cells (or reaches), extending the segment representing the wash further west and upstream toward the WRF. This modification allows for groundwater to seep or leak out of the groundwater system at increasingly upstream locations as water levels rise in response to recharge. The addition of these stream cells also facilitated a more realistic numerical representation of flow rates downstream of Murray Springs.

7. SIERRA VISTA MODEL CALIBRATION AND RESULTS

Calibration is the process of adjusting model parameters to achieve a good match between the simulated and observed hydraulic heads or other relevant hydrologic data such as water budget components. These observed data are called calibration "targets". Initial estimates for hydrogeologic parameters are varied within an observed or estimated range of values to improve the model's ability to simulate these targets.

The range of plausible estimates for hydrogeologic parameters provides constraints on the calibration exercise to ensure that inputs remain defensible and to limit model results to a set of realistic input conditions. The calibration exercise provides confidence that the model is capable of simulating the historical, observed groundwater conditions, and it is completed prior to performing predictive simulations.

7.1 Calibration Approach

The strategy in a transient calibration is to match calibration targets, which represent snapshots of the hydrogeologic system through time. The Sierra Vista Model calibration was examined over several stress periods (or time frames) to ensure that this updated model was within general modeling calibration standards.

A general calibration to 2003 water levels was not documented in the original USGS model report; however, this step was performed by Brown and Caldwell to facilitate a comparison between the localized Sierra Vista Model calibration and the USGS Model from which it was derived. As discussed in Section 4.3, this calibration check also corroborated that the USGS model was within commonly accepted calibration standards.

Calibration of the Sierra Vista Model was primarily focused on improving model agreement with local water levels in the vicinity of the WRF. The ability to reliably simulate the varying hydrologic conditions caused by the artificial and incidental recharge as well as drainage to springs and seeps was an important goal in the calibration exercise. The primary model variable that was adjusted during the calibration of the Sierra Vista Model was hydraulic conductivity, although water level responses to various stream parameters and local water budget components were also investigated.

Calibration of the local water levels to transient observed water levels was achieved by adjusting the hydraulic conductivity values in the immediate vicinity of the WRF. A portion of the 7 m/day zone in Layer 1 directly underlying the eastern WRF was reduced to 4 m/day (Figure 3-3), and the 1 m/day zone in Layer 2 directly underneath the western portion of the WRF was increased to 3 m/day. The new values are consistent with the localized geologic conceptual model for the various aquifer units underlying the facility. As discussed in Section 5.4, a review of borehole cuttings and geophysical logs for BLM Murray wells suggested that fine-grained materials are locally predominant in Layer 1 of the model. Although geologic contact information from the BLM Murray wells could not be definitively correlated with the elevation of fine-grained units underlying the WRF, the reduction in hydraulic conductivity in Layer 1 near the infiltration basins and Murray Springs accounts for the observed fine-grained lithologies. Note that vertical conductance was maintained at the same horizontal to vertical hydraulic conductivity ratio (10:1) as the original USGS model.

7.2 Model Calibration Statistics

Groundwater calibration targets were selected from a compilation of over 5,700 water level measurements, spanning the Sierra Vista Model domain and simulation time period (1986-2008). The locations of these targets are shown on Figure 7-1, and the number of target values used for selected calibration time periods is provided below (Table 7-1).

Calibration statistics for the Sierra Vista Model are provided in Table 7-1 and were evaluated for the time period from 2003 to 2008. Particular attention was paid to matching targets in the vicinity of the WRF, although they were not assigned higher weighting factors than regional data. Local calibration targets included measurements of water levels at WRF and other local monitoring wells as well as recorded flows along the San Pedro River and Murray Springs.

The statistics presented in Table 7-1 are based upon residual values, which represent the difference between simulated and observed water levels. Overall, the calibration of the Sierra Vista Model falls well within the selected calibration criteria of (1) a residual standard deviation (RSD or "root mean square error") that is less than 10% of the total range in observed head and (2) an absolute residual mean (ARM) that is less than 5% of the total range in observed heads. Both criteria for calibration are exceeded for all time periods evaluated. Overall, the calibrated match to local and regionally observed groundwater conditions is excellent over the period of time when recharge activities were occurring at the Sierra Vista WRF. Additionally, the model calibration residuals as well as ARM and RSD statistics are improved relative to the USGS calibration statistics presented in Table 4-2. These calibration metrics support 1) the use of the model as a suitable predictor of future conditions and hydrologic impacts as a result of recharge at the WRF, and 2) the appropriateness of the refinements made to model layering and hydraulic parameters in the vicinity of the Sierra Vista WRF.

Table 7-1. Sierra Vista Model Calibration Statistics

Date	Residual Mean (feet)	Residual Standard Deviation (RSD) (feet)	Absolute Residual Mean (ARM) (feet)	Range in Target Values (feet)	Number of Target Values	ARM / Range	RSD / Range
March 2003	5.99	47.00	21.70	1,256.25	242	1.7%	3.7%
March 2006	-2.63	42.08	17.57	1,112.57	261	1.6%	3.8%
October 2006	-3.13	28.50	15.31	874.14	299	1.8%	3.3%
March 2007	-0.77	24.74	12.98	878.19	290	1.5%	2.8%
October 2007	-0.24	19.33	10.94	266.95	227	4.1%	7.2%
March 2008	-3.73	18.43	10.23	267.80	204	3.8%	6.9%
October 2008	-1.28	12.88	6.64	267.90	161	2.5%	4.8%

7.3 Results

The following sections present simulated groundwater elevations and surface water flows from the calibrated Sierra Vista Model. Simulated water budget components for the model are presented in comparison with predictive simulation results in Section 8.2.2.

7.3.1 Simulated and Observed Water Levels

Simulated water levels in 2008 are presented on Figure 7-1 for the Sierra Vista Model. From a comparison with Figure 4-1, it is apparent that the regional flow regime is virtually identical to that observed and simulated with the USGS Model for 2003; however, there are higher water levels in the vicinity of the WRF due to the artificial recharge. Regionally, flow generally proceeds from the south and from the surrounding mountain ranges toward and along the San Pedro River corridor. Groundwater gradients along the course of the river are generally flatter relative to the perimeter of the basin and are directed northward (downstream of the San Pedro River). A cone of depression is simulated west of the WRF, and corresponds with the historically observed cone of depression west of Sierra Vista and Huachuca City. In the vicinity of Sierra Vista and the WRF, groundwater gradients are generally flatter than that observed in the rest of the basin and flow is locally directed toward both the cone of depression to the west and the San Pedro River to the east. This flatter gradient is caused by the presence of groundwater "sinks" on both sides of the WRF, namely the historic and current pumping associated with the cone of depression and leakage to the San Pedro River and tributary surface water features. The result is a groundwater "ridge" near the WRF and Sierra Vista.

In the vicinity of the Sierra Vista WRF, simulated water levels match the flow description provided in Section 2.5 with a radially diverging flow pattern around the recharge basins and treatment wetlands. Water levels generally decline along a steep gradient from over 4,200 feet amsl immediately beneath the recharge basins to approximately 4,180 feet amsl within a one-mile radius. For comparison purposes, groundwater elevations within the center of the cone of depression fall below 4,130 feet amsl. The influence of the cone of depression upon water levels immediately west (within two miles) of the WRF can be seen on the map inset of Figure 7-1 as an area of significantly lower groundwater elevations. East of the recharge facility, water levels drop off rapidly, approaching the elevation of the San Pedro River bed, as groundwater drains to surface springs, seeps, and as underflow to the river. Simulated depths to water range from over 100 feet one mile west of the WRF, to zero at Murray Springs, less than one mile northeast of the recharge basins. Additional information regarding groundwater mounding and water level impacts is provided in Section 8.2.

In Section 5.3, Table 5-4 presented a comparison of observed versus simulated water levels for 2003 using the original USGS model. Table 7-2 below illustrates the improved water level agreement in the vicinity of the WRF after calibration of the Sierra Vista Model. The USGS Model exhibited water levels ranging from 6 feet above to 22 feet below observed water levels, with water levels significantly under-predicted at monitoring wells WRF-02 and WRF-06 (Figure 1-2). After the calibration process, the Sierra Vista Model now simulates in a range from 7 feet above to 8 feet below observed water levels at the WRF, and also effectively reproduces the magnitude of groundwater rise in the vicinity of the WRF from 2002 through 2008. Additionally, there is good agreement with water levels from nearby monitoring wells included in ADWR's GWSI database.

Data from these wells, located on Figure 5-1, exhibit a slightly larger range in water level differences from model simulation results relative to the WRF wells; however, wells located closer to the WRF have the highest level of agreement. The largest water level difference between observed and simulated conditions in 2008 is for GWSI well “313341110132101”, which is located over a mile from the western boundary of the Sierra Vista WRF, is screened within a different model unit than that where the WRF recharge basins are located, and is influenced more by the adjacent cone of depression. Given the scope of this work, the model simulated water levels at all wells located at or within two miles of the WRF are within an appropriate degree of accuracy.

Table 7-2. Sierra Vista Model: Simulated vs. Observed Water Levels

Well	Current Water Level* (December 2008) (ft amsl)	Model-Simulated Water Level (October 2008) (ft amsl)	Water Level Difference** (feet)
WRF-01	4,205	4,200	5
WRF-02	4,212	4,214	-2
WRF-03	4,199	4,192	7
WRF-04	4,168	4,173	-5
WRF-05	4,165	4,173	-8
WRF-06	4,217	4,216	1
MUR-PER	4,176	4,174 (Layer 1)	2
ADWR GWSI 313341110132101	4,142	4,163	-21
ADWR GWSI 313425110115401	4,185	4,175	10
ADWR GWSI 313506110113301	4,146	4,149	-3
ADWR GWSI 313421110121401 (USGS)	4,169	4,170	-1

**December 2008 or closest water level reading at that location*
***Observed minus model-simulated water level*
Ft amsl = feet above mean sea level

7.3.2 Simulated and Observed River and Spring Flow

Table 7-3 below compares observed streamflow at Murray Springs, the Charleston gage, and the Tombstone gage versus the Sierra Vista Model-simulated baseflow over time. In Section 5.2.4, Table 5-3 presented a comparison of streamflow at Murray Springs and the Charleston stream gage versus model-simulated flows in the USGS model. Observed streamflow at the San Pedro stream gages shown in Table 7-3 represents winter 2007 flow and was calculated as a 30-day median flow; these values include baseflow as well as any runoff contributing to the system. Model-simulated streamflow is from the end of the winter stress period and is representative of only baseflow. As such, the model is able to adequately simulate the contribution of groundwater to baseflow at

Murray Springs, but is not able to reflect the full amount of flow in the San Pedro River for every month. However, from inspection of USGS streamflow records, observed median conditions in the San Pedro generally approach simulated values by the month of May, when flow conditions approach baseflow levels once again. Overall, the Sierra Vista Model was able to more accurately simulate the increased flow at Murray Springs relative to the USGS Model, while maintaining a similar accuracy in simulating San Pedro River flows. This improvement in the ability to simulate flows at Murray Springs is primarily due to the inclusion of additional, upstream "stream package" cells in the Sierra Vista Model, which allows groundwater to contribute to temporally variable spring flow at more spatially accurate locations.

Although the inability of the Sierra Vista Model to simulate both runoff and baseflow conditions in the San Pedro on a monthly basis is a limitation of the model, as well as a limitation in using MODFLOW and its associated packages, these limitations are not believed to substantially affect the predicted, relative impacts to future San Pedro River baseflow as a result of recharge at the WRF. However, future climatic and precipitation conditions will likely cause variations from the overall magnitudes of the predicted flows presented in this study.

Table 7-3 Sierra Vista Model Simulated vs. Observed River and Spring Flow

Location	Observed Streamflow Measurements Winter 2007 (cfs)	Model-Simulated Baseflow March 2007 (cfs)
Murray Springs Flow	0.34	0.5*
San Pedro Streamflow (Charleston Gage)	14.1	4.5
San Pedro Streamflow (Tombstone Gage)	12.0	7.9

**This value represents flow from same model-simulated cell as reported in Table 5-3; however, simulated flow also begins one cell upstream at a rate of 0.07 cfs in the Sierra Vista Model in March 2007*

8. PREDICTIVE SIMULATIONS

Predictive simulations using the Sierra Vista Model begin in October 2008 and extend to October 2040. They are represented by 65 seasonal stress periods, covering 32 years of future conditions. The final 2008 head distribution from the calibrated 1986 to 2008 Sierra Vista Model became the initial heads for the predictive simulations.

The impacts of WRF recharge on future groundwater levels and flows at Murray Springs and in the San Pedro River were evaluated. Impacts are defined as the future predicted changes in water levels or streamflow that are attributable to recharge from the Sierra Vista WRF infiltration basins and wetlands. These impacts are reflective of both water level and flow increases as well as offsets to future predicted water level declines and flow depletions simulated in the absence of WRF recharge. The time periods for which impacts were evaluated include October 2007, 2012, 2017, 2022 and 2040, in accordance with the BOR cooperative agreement.

8.1 Predictive Scenarios

Two primary, predictive scenarios were performed to estimate the impact of recharge from the WRF. Both scenarios hold groundwater withdrawals, evapotranspiration, recharge (other than WRF recharge), and stream and boundary condition parameters at their March 2008 and October 2008 values for all summer and winter seasons, respectively. The only difference between the two scenarios involves the presence of artificial recharge from the Sierra Vista WRF in the future. This approach was taken to calculate the impact of the WRF recharge upon water levels and surface water conditions without the impacts of changing groundwater demands, climatic conditions, or other recharge sources obscuring the results.

The first scenario (termed the “Recharge Scenario”) assumes that the current magnitude of infiltration basin recharge at the City’s WRF, or an average annual rate of 3.2 MGD, would continue from present day through 2040. Seasonal recharge rates at the WRF are also held constant through 2040 at the same levels applied in the final two model seasons ending in March 2008 and Oct 2008. Assumed incidental recharge at the wetlands is held constant at 800 AFY. Annual estimated recharge for the WRF basins and wetlands totals approximately 2,839 AFY for the predictive time period. This recharge total is slightly different than that stated previously in Section 5.2.1 because the most recently recorded monthly recharge volumes for the seasonal time periods were summed to produce this value in lieu of an annual total.

The second predictive scenario (termed the “No Recharge Scenario”) was simulated to generate a “baseline” condition for the evaluation of the WRF’s impact on water levels, spring flow, and streamflow. This scenario assumes that artificial recharge at the WRF ceases after October 2008 and reverts back to seasonal, background levels through 2040. Although it is not realistic to assume that there will be no recharge activities at the WRF through 2040, this simulation was performed to produce water level and streamflow distributions for direct comparison with results from the first scenario. The comparison of the results from the simulation of both scenarios provides the means to calculate predicted impact of WRF recharge.

An additional simulation was also performed with basin recharge set at the full permitted recharge capacity of 4.0 MGD. However this simulation produced estimated water levels that reached ground surface at the infiltration basins before 2040. Given these results, the current trend in decreasing WRF recharge volumes presented in Table 5-2, and current City plans for future treatment and recharge facilities, the current recharge rate of 3.2 MGD was deemed to be most appropriate for estimating future hydrologic impacts.

8.2 Predictive Simulation Results

The following sections detail the simulation results for the two predictive scenarios including the estimated future impacts of WRF recharge on regional aquifer water levels and baseflow at Murray Springs and the San Pedro River.

8.2.1 Impact of WRF Recharge

Evaluation of the benefits provided by the WRF to the regional aquifer and associated surface water bodies involved the definition and calculation of "impact". Impact was defined as the change in simulated water levels and surface water flows at a given future time as a result of WRF recharge. It was calculated by subtracting the simulated water levels and streamflows from the No Recharge Scenario from the Recharge Scenario for each relevant model cell at various future times. This analysis of impact not only takes into account absolute water level rise and streamflow increases due to the WRF but it also considers regional hydrologic declines that would occur if the WRF did not exist. In essence, this calculation illustrates the full benefit of the WRF on the local aquifer system as opposed to a more common drawdown or water level rise calculation. Note that the impacts discussed in the following sections represent the hydraulic benefits to the aquifer system, and do not represent the estimated migration distances of the recharged water.

8.2.1.1 Water Level Impact Maps

Figures 8-1 to 8-4 illustrate the calculated impact of the WRF recharge on the groundwater conditions in 2012, 2017, 2022, and 2040. The spatial distributions of impact were restricted to areas estimated to be greater than 1 foot. This does not imply that the model has this level of accuracy, rather it was used only as a minimum unit of measure to assess the maximum potential spatial extent and trends in impact. As observed on Figure 8-1, by 2012 the impact of the WRF recharge has spread in an approximately 2-mile radius with a maximum impact of approximately 58 feet occurring beneath the recharge basins. As observed on Figure 8-2, by 2017 the impact of WRF recharge has increased to approximately 4 miles west of the WRF with maximum impact of approximately 68 feet underneath the recharge basins. The apparent bias of the impact in a westerly direction is due primarily to groundwater outflows at Murray Springs and other surficial drainages, which drain water from the groundwater mound, limiting the eastern extent of water level impacts. Essentially, the area east of the WRF has a much thinner vadose zone to store the recharge water, and it must locally discharge to ground surface at springs and seeps.

As seen on Figure 8-3, by 2022 the impacts of the WRF recharge on water levels stretch further to the west and southwest of the facility, extending approximately 5.5 miles from the facility with a maximum impact of 73 feet beneath the recharge basins. Again, the effects of springs restrict water level impacts from extending further east. However, some positive impact is evident immediately east of the Murray Springs location as a portion of the induced increase in spring flow recharges the surficial aquifer before reaching the San Pedro River. By 2040 (Figure 8-4), after approximately 38 years of WRF recharge at an annualized rate of 3.2 MGD, the impact of the WRF has spread approximately 8 miles to the west, 3.5 miles to the north, 9 miles to the south and 3 miles to the east. A maximum impact of approximately 83 feet occurs underneath the recharge basins. Seepage to surface water features, including the San Pedro River, continues to restrict the extent of water level impacts to the east, and mountain front recharge and steep groundwater gradients from the Huachuca Mountains force the spread of water level impacts to the northwest and southwest of the WRF.

As viewed on Figures 8-1 through 8-4, the greatest positive impacts to water levels from groundwater recharge at the Sierra Vista WRF are located in close proximity to the recharge basins. However, the predicted spread of all beneficial water level impacts extends more than 8 miles to the west of the WRF by 2040. By comparing the estimated water level contours and impact distribution in 2040 (Figure 8-4), it is apparent that estimated future water level impacts will help counter-balance groundwater declines throughout the majority of the areal extent of the cone of depression. The magnitude of the predicted beneficial impacts are typically less than 10 feet for the bulk of the cone of depression, but the magnitude increases dramatically approaching the eastern boundary of the WRF.

Although the predicted beneficial impacts to water levels in the vicinity of the WRF increase over time, simulated water level elevations continue to decline in some portions of the basin. From a comparison of water level contours for 2040 and 2008 shown on Figure 8-4 and Figure 7-1, respectively, the cone of depression west of the WRF, denoted by the closed water level contours and associated water level divides on the inset maps, persists and expands even though positive impacts of WRF recharge are simulated. This suggests that although recharge from the WRF is able to locally induce rises in the water table, it can only partially offset groundwater declines more distal to the facility.

An additional benefit to current and future recharge simulated at the WRF includes the formation of a groundwater mound. This mound is defined by the area in which groundwater elevations are estimated to rise by 2040 relative to current conditions (as of 2008). The lateral extent of positive water level changes (or mounding) associated with WRF recharge is shown as a color flood on Figure 8-5 along with estimated water levels in 2040. The mound is located approximately equidistant between the San Pedro River and the cone of depression and is estimated to extend approximately four miles in a north-south direction. This predicted distribution of groundwater rise would essentially limit the eastward spread of the cone of depression, and its associated water level declines, within shallow aquifer units most directly in contact and communication with the San Pedro River. The mound is predicted to extend approximately one mile west of the recharge basins and approximately 2 miles north and south of the WRF. Additional, smaller water level rises are also simulated to the east of the WRF and along the course of the San Pedro River; however, these rises are estimated to be very small and are constrained by the shallow depth to the water table along the San Pedro River corridor and its associated tributary drainages. The presence of this mound supports the concept that the cone of depression is not predicted to expand eastward in the vicinity of the Sierra Vista WRF due to the artificial groundwater recharge. The impact of groundwater mounding associated with WRF recharge on surface water flow conditions is discussed in the following sections.

8.2.1.2 Murray Springs Flow

Table 8-1 presents the observed spring flow at Murray Springs in winter 2007 as well as model-simulated spring flow during the winter time period in 2007, 2012, 2017, 2022, and 2040. In 2007, the model closely matches observed spring flow. By 2012, simulated spring flow has almost doubled and continues to increase slightly through 2022. However, simulated flows have essentially stabilized by 2012.

Although not a focus of this study, other springs in the area were also simulated to have positive impacts to flow over the predictive time period. These increases were gradual and much smaller in magnitude than those simulated for Murray Springs, which is consistent with the conceptual model for the local study area presented in Section 5.2.3.

Table 8-1. Model-Simulated Spring Flow Results

Location	Observed Streamflow Measurements Winter 2007 (cfs)	Model-Simulated Baseflow March 2007 (cfs)	Model-Simulated Baseflow Winter 2012 (cfs)	Model-Simulated Baseflow Winter 2017 (cfs)	Model-Simulated Baseflow Winter 2022 (cfs)	Model-Simulated Baseflow Winter 2040 (cfs)
Murray Springs Flow	0.34	0.5	0.9	1.0	1.1	1.1

8.2.1.3 San Pedro Streamflow

Figures 8-6 to 8-9 illustrate the impacts to simulated San Pedro River baseflow due to the Sierra Vista WRF recharge. Streamflow impacts (greater than 0.2 cfs) in 2012 demonstrate that significant, positive impacts to streamflow essentially begin at Murray Springs and continue downriver to the model boundary at the Tombstone stream gage (Figure 8-6). The maximum estimated impact to streamflow in 2012 was approximately 0.45 cfs at the Tombstone gage with similar impacts occurring along the course of the San Pedro River downstream of the WRF. Minor positive impacts (less than 0.2 cfs) to streamflow are also seen along the Babocomari Wash north of the WRF and at smaller springs located north (Moson Spring) and south (Horse Thief Spring) of Murray Springs. As seen on Figure 8-7, a similar impact pattern is evident by 2017, with the most significant increases beginning at Murray Springs and continuing downstream along the San Pedro River to the Tombstone stream gage. Maximum, simulated streamflow impact has increased to approximately 0.85 cfs at the Tombstone gage by this time. As seen on Figure 8-8 and Figure 8-9, maximum simulated streamflow impact at the Tombstone gage increases to approximately 0.96 cfs by 2022 and to approximately 1.4 cfs by 2040. The distribution of streamflow impacts along the San Pedro River and at the various springs remains similar for these two future time periods. The small magnitude impact to streamflow observed near the southern model boundary at the Palominas stream gage is attributed to small numerical instabilities with the stream package in that localized area. Lastly, a comparison of simulated streamflow impact maps (Figure 8-6 through Figure 8-9) with the estimated groundwater impact maps (Figure 8-1 through Figure 8-4) illustrates the previously discussed point that discharge to surface water features limits the eastern extent of beneficial water level impacts from WRF recharge; however, this is counterbalanced by the beneficial impacts to flows in local springs and along the northern reaches of the San Pedro River.

Table 8-2 presents actual measured streamflow and simulated baseflow for both the Charleston and Tombstone stream gages. Observed streamflow measurements are represented by the 30-day median value for March 2007. Although the measured streamflow values are significantly greater than those simulated in the Sierra Vista Model, this is attributed to the fact that the stream package only considers baseflow and does not explicitly consider runoff from precipitation events or snowmelt. However, measured streamflow values for the months of April and May, which are more representative of spring baseflow conditions in the San Pedro River, are of a similar magnitude as those simulated by the Sierra Vista Model for March 2007. As previously noted in Section 3.2.8, although the model is not capable of simulating the magnitude of observed streamflow for every point in time, it is believed to adequately simulate baseflow conditions and changes or impacts to baseflow along the San Pedro River and other surface water features. The suitability of the model is further demonstrated by its ability to adequately simulate the magnitude of flow from Murray Springs, which is dominated by baseflow from groundwater.

Similar to the simulated spring flow trends at Murray Springs, simulated San Pedro baseflows exhibit the largest increase between 2007 and 2012 and then begin to stabilize. Note that for both the San Pedro River and Murray Springs (Table 8-1) there are increasingly positive impacts to streamflow over time due to recharge at the WRF even though the simulated flow magnitudes stabilize over time. This is due to the fact that the No Recharge Scenario simulates declines in streamflow given the conditions assumed for the predictive time period. Recharge at the WRF is estimated to essentially induce an initial increase in streamflow as well as offset potential future declines.

Table 8-2. Model Simulated Streamflow Results

Location	Observed Streamflow Measurements March 2007 (cfs)	Model-Simulated Baseflow March 2007 (cfs)	Model-Simulated Baseflow March 2012 (cfs)	Model-Simulated Baseflow March 2017 (cfs)	Model-Simulated Baseflow March 2022 (cfs)	Model-Simulated Baseflow March 2040 (cfs)
San Pedro Streamflow (Charleston Gage)	14.1	4.5	5.0	5.1	5.2	5.1
San Pedro Streamflow (Tombstone Gage)	12.0	7.9	8.3	8.4	8.4	8.2

8.2.2 Simulated Water Budget

The simulated water budget for the Sierra Vista Model in 2008 and at the end of the predictive time period in 2040 is presented in Table 8-3. Water budget components that exhibit the largest changes from 2008 to 2040 include storage, fluxes from constant head cells, stream leakage, and evapotranspiration. Although there is a significant reduction in inflow from storage (depletion of aquifer reserves) there is also a reduction in outflows to storage (addition of water to aquifer reserves) that partially offsets this change. Given the size of the model domain, the overall change in storage is less useful in evaluating the influence of the WRF recharge than the previously discussed groundwater and streamflow impacts. However, the addition of recharge from the WRF does locally reduce groundwater depletions and adds water to the aquifer system. A simulated increase in inflows from constant head cells occurs along the southern model boundary near Naco, Arizona in the extreme southeast corner of the model domain; however, this is not believed to bias estimated water levels in the vicinity of the WRF.

Table 8-3. Sierra Vista Model Water Budget Comparison: 2008 versus 2040

	Sierra Vista Calibrated Model Spring/Summer 2008 (Stress Period 45)	Sierra Vista Predictive Model Spring/Summer 2040 (Stress Period 64)
Inflows		
Recharge	16,219	16,219
Stream Leakage	4,171	4,408
Storage	14,770	11,900
Constant Head	5,356	6,882
Total	40,516	39,409
Outflows		
Constant Head	2,208	1,915
Pumping (Net)	17,767	17,742
Drains	437	431
Evapotranspiration	12,454	13,029
Stream Leakage	5,685	6,049
Storage	2,033	307
Total	40,584	39,473

AFY = acre-feet per year

The changes in simulated stream leakage and evapotranspiration are likely influenced by recharge from the infiltration basins and treatment wetlands. Stream leakage into the aquifer system increases slightly due to the increased flows in local springs and the San Pedro River downstream of the WRF. Likewise stream leakage from the groundwater system into surface water features also increases due to the estimated increased baseflows in both the San Pedro River and Murray Springs. The estimated increase in leakage into and out of stream features over time (237 AFY and 364 AFY, respectively) suggests that the beneficial impacts of the WRF artificial recharge are generating several hundred acre-feet per year of water that is available to the local surface water system. The increase in evapotranspiration also suggests that the additional streamflow and groundwater rises induced by the WRF recharge has the potential to enhance riparian vegetation along the northern reaches of the San Pedro River.

Although the results of the predictive simulations suggest that there are significant benefits of local recharge to flows in the San Pedro River and riparian vegetation along its course, additional refinements to the model are required to more accurately quantify the magnitude of these impacts at specific locations and time periods.

8.2.3 Particle Tracking - 2040

Particle tracking using MODPATH (version 3) was performed over a portion of the predictive model's time frame to estimate the flow directions and travel time of water derived from the recharge basins. Particle tracking provides an estimate of travel time for recharge water to reach a specific location, i.e. Murray Springs, as opposed to the impact maps and discussions presented in prior sections. Because of the large size of the output files from the Sierra Vista Model, a 10.5-year subset of the Recharge Scenario was used for a particle tracking analysis, beginning in October 2008 and continuing until March 2019; however, future model modifications (including limiting the model domain to the vicinity of the WRF, cone of depression and adjacent San Pedro River to reduce digital file size constraints) would permit longer particle tracking simulation times. Additionally, because particle tracking models are sensitive to aquifer layering and hydraulic parameters such as permeability and porosity, it would be beneficial to refine model layering and parameterization in future model revisions to improve predictions of the migration of recharged water.

A circle of 20 particles surrounding the recharge basins was placed in Layer 1 of the model. An additional circle of 15 particles was placed on top of the wetland cells in order to generally assess the influence of the incidental recharge as well as the change in uppermost layer and hydraulic conductivity values between the recharge basins and wetland cells. Porosity was assumed to be 0.1 for the entire model. This value was selected based upon observed and documented lithology and geologic layering in the vicinity of the WRF and Murray Springs, but it could be refined with additional field measurements. Note that particle tracking models are very sensitive to porosity estimates, and variations in this value can substantially change predicted estimates of travel times. Particles were set to pass through weak sinks as long as the discharge out of the cell was greater than half the inflow to the cell.

Figure 8-10 illustrates the particle tracking results. The mounding effect typical of recharge sites is apparent in the radial flow pattern of the particle traces. The additional mounding caused by the 800 AFY of incidental recharge from the wetland treatment cells as well as the reduction in hydraulic conductivity between the recharge basins and the wetland cells forces the westernmost flow paths from the recharge basin to be deflected to the north or south. The maximum travel distance for recharged water from the infiltration basins over the 10.5-year simulation period was approximately one mile. Because particle tracing analyses represent conservative, non-dispersive transport of solutes, it is possible for a fraction of the recharged water to travel further over the same time period.

Color coding on the particle traces represents time increments for the migration of simulated particles (Figure 8-10). Recharge water from the WRF is simulated to take approximately 8 or more years to reach the location of Murray Springs. Note that the particle tracking model began in 2008 when a groundwater mound was already present beneath the recharge basins and a steeper gradient already exists, thereby increasing groundwater flow velocities. If particles had been released in 2002, at the start of the WRF facility, it is likely that particle travel times to Murray Springs would be longer.

Lastly, only one of the particle traces reaches Murray Springs during the simulation time period. A different arrangement of particles at the infiltration basins may be able to induce the flow of another particle trace to Murray Springs; however, it is unlikely that three traces would reach this location unless additional particles are added. Given the fact that 20 particles were released around the recharge basins and into the model, it is estimated that the percentage of recharged water being discharged at Murray Springs after 10.5 years is between 10% and 15%. This rough approximation compares favorably with the estimated 8% to 10% of induced flow at Murray Springs in 2008 due to WRF recharge (see Section 5.2.3).

9. CONCLUSIONS

Based upon reviews of previous models, conceptualization of local study area conditions, development and calibration of the Sierra Vista Model, and simulation of future impacts of WRF recharge on groundwater conditions and San Pedro River flows; the following conclusions were drawn for this study:

1. The updated USGS Model provides a suitable basis for the Sierra Vista Model. Refinements made to layering, hydraulic parameters, and distribution of stream cells in the Sierra Vista Model permitted the successful calibration to observed groundwater and surface water conditions in the vicinity of the WRF. Calibration results indicate that the Sierra Vista Model is a viable tool for assessing future hydrologic conditions in the subwatershed.

2. Recharge from the Sierra Vista WRF infiltration basins and treatment wetlands has caused 1) a water level mound underneath and immediately adjacent to the infiltration basins and 2) increased flows at nearby Murray Springs comparable to approximately 8 to 10 percent of average annual recharge at the WRF.

3. Predictive simulations performed with the Sierra Vista Model demonstrate that the continued recharge of 3.2 MGD at the WRF will satisfy major goals of the BOR demonstration project by (1) partially offsetting declines in the neighboring cone of depression to the west and (2) creating a localized groundwater mound that will aid in protecting portions of the San Pedro River from the effects of groundwater withdrawals.

4. By 2040, positive impacts on water levels are estimated to extend approximately 5.5 miles to the northwest and southwest of the WRF, with a maximum impact predicted to exceed 70 feet beneath the infiltration basins by 2040. The groundwater mound (water level rise) from WRF recharge is simulated to extend more than 3 miles in a north-south direction by 2040, and has a stabilizing effect on the pumping cone of depression in the uppermost aquifer units. Discharge from the groundwater system to Murray Springs, other local springs, and the San Pedro River limits the future rise of water levels in the aquifer to the east of the WRF. This groundwater leakage to surface water features directly supports and augments future baseflows in the San Pedro River.

5. As a result of WRF recharge, spring flow at Murray Springs is estimated to increase from its present-day flow rate of 0.34 cfs to 0.9 cfs by 2012; then stabilize at a rate of 1.1 cfs between 2012 and 2040.

6. Predictive simulations performed with the Sierra Vista Model demonstrate that past and future recharge at the WRF will satisfy a major goal of the BOR demonstration project by sustaining and augmenting flows in the San Pedro River. The maximum positive impact on flow in the San Pedro River is estimated to be approximately 1.4 cfs at the Tombstone gage by 2040, including both potential increases in river flow as well as offsets to future streamflow depletions since 2008.

7. From a comparison of estimated streamflow impacts and simulated water budget changes in the model, the percentage of recharge benefiting spring flow, streamflow and riparian vegetation along the San Pedro River is estimated to be approximately 30% to 40% by 2040. This percentage corresponds well with the estimated 40% to 50% of artificial recharge over 50 years estimated by the USGS for the general location of the WRF (Leake et al., 2008).
8. A particle tracking analysis performed for WRF recharge water shows recharge migrating approximately one mile away from the WRF in 10.5 years and reaching Murray Springs approximately 8 years or more after infiltrating to the water table. The results for this analysis have a large amount of uncertainty associated with them; however, they do correspond with the local scale conceptual model and observed conditions.
9. The WRF recharge basins are very well situated to benefit both local and regional groundwater elevations as well as future baseflow in the San Pedro River. From simulated impacts to streamflow, evapotranspiration and water levels, it is estimated that the recharged water at the WRF benefits both the regional aquifer and San Pedro River system in similar proportions.
10. Results of predictive simulations conducted with the Sierra Vista Model show that recharge at the Sierra Vista WRF satisfies the key objectives of the BOR demonstration project by protecting regional groundwater reserves and maintaining and augmenting flows along the San Pedro River. Future recharge and water management projects, if also properly planned and located, have similar potential to create beneficial impacts to hydrologic conditions in the Sierra Vista Subwatershed.

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FIGURES

APPENDIX Z

Report, Electronic Model Files, and GIS Database (CD In Pocket)