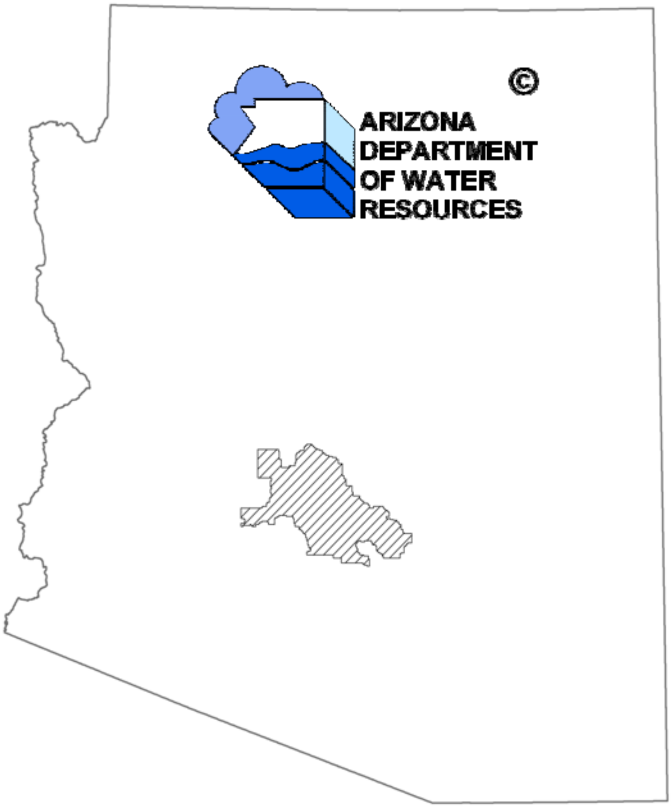
ARIZONA DEPARTMENT OF WATER RESOURCES

REGIONAL GROUNDWATER FLOW MODEL OF THE SALT RIVER VALLEY PHOENIX ACTIVE MANAGEMENT AREA MODEL UPDATE AND CALIBRATION



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MODELING REPORT NO. 19

APRIL 2009

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List of Acronyms

AAWS	Assured and Adequate Water Supply
ADWR	Arizona Department of Water Resources
AMA	Active Management Area
AME	Absolute Mean Error
BAS	Basic Package
BCF	Block-Centered Flow Package
BLS	Below Land Surface
CAP	Central Arizona Project
CHB	Constant Head Boundary
CHD	Time-Variant Specified-Head Package
CTA	Current Trends Alternative Analysis
DIS	Discretization Package
DTW	Depth to Water
ET	Evapotranspiration
GFR	Grandfathered Right
GMG	Geometric Multigrid Solver package
GRIC	Gila River Indian Community
GRUSP	Granite Reef Underground Storage Project
GWSI	Groundwater Site Inventory
HOB	Hydraulic-Head Observation Package
HMS	Hydrologic Map Series
HYDMOD	MODFLOW Hydrograph program
IBW	Indian Bend Wash
IGFR	Irrigation Grandfathered Rights
K	Hydraulic Conductivity
LAU	Lower Alluvial Unit
MAU	Middle Alluvial Unit
ME	Mean Error
RCH	Recharge Package
RMSE	Root Mean Squared Error
ROGR	Registry of Grandfathered Rights
RID	Roosevelt Irrigation District
SCIP	San Carlos Irrigation Project
SFR	Stream Flow Routing Package
SRP	Salt River Project
SRPMIC	Salt River Pima-Maricopa Indian Community
SRV	Salt River Valley
UAU	Upper Alluvial Unit
USBR	United States Bureau of Reclamation
USF	Underground Storage Facilities
USGS	United States Geological Survey
VCONT	Vertical Conductance
WEL	Well Package
WWTP	Waste Water Treatment Plant

Abstract

Managing regional aquifer systems within the arid southwestern U.S. basins requires an understanding of the extent to which aquifer recharge and withdrawal impacts the systems, both spatially and temporally. One of largest managed aquifers in Arizona is the Salt River Valley (SRV) located within the Phoenix Active Management Area (AMA). Groundwater modeling has become the primary tool hydrologists and water resource managers rely on when examining the regional impacts of future water use scenarios within the SRV.

In 1994, the ADWR completed the first ADWR groundwater flow model for the SRV. The SRV MODFLOW groundwater model has undergone multiple updates since it was first published in 1994. ADWR has revised the SRV model to reflect changes in the following: spatial and temporal extents, inflow and outflow datasets, deliverables, and recalibration. The 2009 SRV model update is based on the same conceptual principles as previous models; however, each component of the water budget was re-examined and updated where deemed appropriate by the ADWR. The updated model has improved calibration in regards to residual heads and water budgets.

The 2009 SRV model update includes the following improvements: simulates conditions between 1983 and 2006, decreases the model cell size to 0.5 mile by 0.5 mile, updates geologic interpretation, adds the Lake Pleasant region, revises pumpage and recharge datasets, and uses an updated MODFLOW code. In addition to the model updates, the model was re-calibrated using well specific heads and the annual water budget for the transient period of 1983 to 2006.

The transient calibration was able to simulate regional fluctuations during the 24 year simulation as indicated through the evaluation of well hydrographs, water level contours, and the model water budget. Approximately 93% of the observed heads had a residual error (simulated – observed water level) during the transient period of less than 30 feet. The model calibration was evaluated during three separate basin sweep years (1991, 1997, and 2002). The average absolute weighted residual error was 11 ft. The East SRV generally simulated conditions better than the West SRV. The simulated water budget maintained a zero percent

discrepancy between inflow and outflow and closely matched values developed in the conceptual water budget.

1.0 Introduction

The Arizona Department of Water Resources (ADWR) has developed an updated version of a numerical groundwater flow model for the Salt River Valley (SRV), which is located in the Phoenix Active Management Area (AMA). Since the inception of Arizona's Groundwater Management Act of 1980, the ADWR's focus within the Phoenix AMA has been to manage the groundwater stresses while maintaining a sustainable groundwater supply. The spatial and temporal transformation of population growth, land management, and aquifer stresses within the SRV requires a holistic examination of the study area. The updated SRV model provides an appropriate tool to assist the ADWR Water Management (WM) Division in developing an integrated, comprehensive water management plan for the Phoenix AMA.

1.1 Objective and Scope

The purpose of the SRV model update was to upgrade the previous SRV numerical groundwater model to assist the ADWR with developing scenarios to simulate future water management issues within the Phoenix AMA. In addition to using the SRV model as a predictive simulation tool, the model data serves as a repository of hydrologic and geologic field data. This update does not represent the ADWR's anticipated final improvement to the SRV model, which would require simulating steady-state conditions and adding land subsidence simulation capability in addition to the Hassayampa subbasin area. To improve upon the last SRV model update (1983-2002) the model study was divided into two phases. Phase I updated various components of the regional groundwater flow system conceptual model. The model updates include:

- ✓ Revised geologic interpretation
- ✓ Revised model grid from 1 mile to 0.5 mile grid spacing
- ✓ Added the Lake Pleasant Region to the active model grid
- ✓ Updated pumpage and recharge values
- ✓ Incorporated the latest MODFLOW code

Phase II included recalibrating the regional model, focusing mostly on the updated components to improve the model simulation results in comparison to the observed groundwater levels. The purpose of this report is to provide a brief overview of the SRV model and a detailed analysis of the updates that were made to the model.

1.2 Project Setting

The Phoenix AMA is located in the basin and range physiographic province of Central Arizona. The SRV active model domain consists of approximately 2,505 square miles (mi^2) of the 5,646 mi^2 Phoenix AMA (Figure 1.1). The SRV model area contains portions of the Eloy and Maricopa-Stanfield subbasins of the Pinal AMA, and the East Salt River Valley, Lake Pleasant, West Salt River Valley, and Hassayampa subbasins of the Phoenix AMA. The model domain also includes Arizona’s greatest population density. Figure 1.2 illustrates the urban centers within the SRV model as well as the two Indian communities: the Gila River Indian Community (GRIC) and Salt River Pima-Maricopa Indian Community (SRPMIC). The SRV model domain includes the Superstition, McDowell, Santan, Sierra Estrella, White Tank, and Hieroglyphic Mountains and the Buckeye Hills.

1.3 Previous Investigations

The simulation of the SRV groundwater flow system with the use of a groundwater model began in 1968 with an electric analog model that simulated groundwater depletion between 1923 and 1964 (Anderson, 1968). In 1982 Long *et al.* developed a United States Geological Survey (USGS) two-dimensional Trescott model which simulated conditions from 1964 to 1977. In 1994, ADWR developed a three-dimensional numerical model of the SRV using the USGS MODFLOW code and simulated transient conditions between 1983 and 1988. That effort was documented in ADWR modeling report No. 6 (Corkhill *et al.* 1993) and No. 8 (Corell and Corkhill, 1994). The conceptual design and datasets developed for the 1994 model serve as the foundation for the current SRV model update.

Since the original 1994 SRV MODFLOW model design, two updates have occurred. The updates incorporated more recent water levels, pumping and recharge data, and updated MODFLOW packages and code. In 1991 the Current Trends Alternatives (CTA) model was released, simulating transient conditions between 1983 and 1991 (Hipke *et al.* 1996). In 2004 the SRV MODFLOW model was updated by Bota *et al.* (2004) to simulate conditions between 1983 and 2002. The 2004 update was the catalyst for the development of the current SRV model update that simulates conditions between 1983 and 2006. The 2004 updates included a conversion to MODFLOW 2000 code, flood flow recharge to Salt and Gila Rivers, conversion from the River package to the stream flow routing (SFR) package, and updated aquifer parameters, all of which led to the recalibration of the model.

2.0 Updated Regional Groundwater Flow System Conceptual Model

The conceptualization of the regional groundwater flow system within the SRV has evolved since Thomas Anderson's electric analog analysis which simulated conditions in Central Arizona between 1923 and 1964 (Anderson, 1968). The historic groundwater flow follows an east to west gradient along the Salt River and then Gila Rivers; however, anthropogenic stresses have impacted the system creating localized complexities in the flow regime. To account for localized heterogeneity, the conceptual design of the SRV study area between 1983 and 2006 has been adjusted for this study as a result of additional data, modeling code improvements, modified transient time period, and study area.

2.1 Geologic Interpretation

The definition of the alluvial basin's stratigraphic column is critical for understanding the regional aquifer units. ADWR 2006 re-evaluated the original geologic conceptual design of Corkhill *et al.* (1993) by reviewing approximately 15,600 wells drilled between the early 1980s and 2005 (Dubas and Davis, 2006). Of the 15,600 wells, 860 wells provided pertinent data in the form of geologists' logs, geophysical logs, particle-size logs, fines logs, and drillers' logs from which information was obtained regarding unit contacts and bedrock depth.

The original geologic conceptual design divided the SRV model's alluvial basin-fill deposits into three separate layers. The ADWR unit definitions outlined by Corell and Corkhill (1994) differ slightly from those previous defined by the United States Bureau of Reclamation (USBR) and the USGS. The three separate layers, in descending order, are the upper alluvial unit (UAU), middle alluvial unit (MAU), and the lower alluvial unit (LAU). The three units' thicknesses differ depending on bedrock elevation throughout the basin. The geologic interpretation and definition of the three separate layers was re-evaluated in 2006 by

Dubas and Davis (2006). According to Dubas and Davis (2006) the UAU is defined by gravel, sand, and silt. The MAU is defined by clay, silt, mudstone, and gypsiferous mudstone. The MAU characteristics merge with the other units near the margins of the basin. The LAU is defined by conglomerate and gravel near the basin margins, transitioning into mudstone, gypsiferous and anhydritic mudstone, and anhydrite in the basin centers. The LAU overlies the bedrock unit. To differentiate the three layers, the MAU was defined by counting the frequency and thickness of fine-grained samples. The MAU was required to contain at least 40 percent clay and/or silt and have a total thickness of at least 60 feet. Seven geologic cross-sections within the SRV model domain were constructed (Figures 2.1, 2.2, and 2.3) to illustrate the variation in the ADWR MAU model layer definition.

The west and east SRV groundwater subbasins are separated by a section of shallow pediment surfaces and exposed bedrock consisting of the Union Hills, Phoenix Mountains, and Papago Buttes (Figure 2.4). The eastern portion of the SRV contains the deepest total sedimentary thickness (>2,750ft) near the town of Gilbert and city of Chandler with a deep trough extending northwest towards the city of Scottsdale (Figure 2.4). The deepest sedimentary thicknesses occur in the northwest corner of the SRV both north and east of the White Tank Mountains near the cities of Peoria, Surprise, and Litchfield (Figure 2.4).

The thickness and geologic unit contacts were translated into depth contours, with each model node assigned a land surface, UAU, MAU, and LAU bottom elevation. The SRV model update required adjustments to the conceptual design to improve the interaction with the USGS MODFLOW code. One adjustment was the result of the geologic unit contouring methodology along the hardrock boundaries. Since the publication of ADWR Report No. 16 discrepancies were found in the vicinity of the White Tank Mountains, South Mountain, and the San Tan Mountains regarding the automated translation of geologic data into elevation contours and discretization into the model grid. In many instances a hydrogeologic unit's thickness remained constant or increased where intersecting the hardrock. For example, the contours indicated the thicknesses between the hardrock and the closest contour line were increasing when they should have been decreasing. After a thorough review of the available drill logs in those areas, the geology data for the cells affected were manually changed to reflect the results of that review. As with the original SRV model, the total simulated thickness of hydrogeologic units was truncated at a depth of 3,000 feet below land surface (BLS). This was selected since few wells exist below that depth.

In addition to adjusting model layer surfaces near hardrock boundaries, areas exist in the model domain that were interpreted based on few or no data (Figure 2.5). Within many of these data deficient areas, little change was made to the geologic interpretation as defined by the 1994 SRV model. Additional geologic investigations have taken place by various entities, particularly in the West SRV since the completion of the ADWR Report No. 16 in August 2005. While these data may slightly modify the current model layer geometry in some locations, the ADWR SRV model update will utilize the geologic update through 2005, because it presents the most complete interpretation for the entire study area. Data collected since 2005 will be applied to future model updates.

2.2 Hydraulic Properties

The ability for the aquifer to transmit water is governed by the aquifer's storage and hydraulic conductivity properties. Hydraulic conductivity (K) was originally conceptualized for each geologic unit using aquifer test data from various sources (Corell and Corkhill, 1994). Since the original model conceptualization, the K values along the Salt River corridor and within the City of Chandler area were modified during the 2004 SRV model update based on previous studies for the Granite Reef Underground Storage Project (GRUSP) and studies conducted by Southwest Groundwater Consultants and Clear Creek Associates (Bota *et al*., 2003).

The initial K distribution for each per hydrogeologic unit generally relied on the values used in the previous ADWR model update (2004). The only modification was a result of the updated geologic interpretation that altered the saturated thickness throughout the model. To compensate for the change in saturated thickness while still honoring the 2004 SRV model update's total transmissivity (T) values, new K's were determined using the 2004 SRV model update's transmissivities and the current layer thicknesses. The new K values within the UAU vary from 1 foot per day (ft/day) to 200 ft/day. The areas of high K are located along the SRV river corridor that is typically defined by highly permeable materials such as sand and gravel. The MAU and LAU have a similar spatial trend; only with a lower K_v value.

The specific yield values were not changed from the previous ADWR model update (2004), with the exception of the Lake Pleasant area that was added during the current update. The specific yield for the SRV study area ranged between 7 and 12 percent for the UAU, MAU, and LAU. The Salt and Gila River corridors (UAU only) have specific yield values between 13 and 20 percent.

2.3 System Inflow

System inflows are defined as flow components within the SRV model area that contribute water to the regional aquifer. These components include recharge (natural and incidental) and underflow from areas outside the study area (Figures 2.6 and 2.7). The conceptualized spatial and temporal distribution of groundwater inflow relies on long term average water volume.

2.3.1 Underflow

Groundwater underflow volumes into the system were originally derived by Corkhill *et al*. (1993) from examining water level gradients, developing a flow net analysis using predevelopment conditions, and applying the results of previous transient modeling. The total underflow into the system was estimated at 31,800 acre-feet/year based on previous studies by Corkhill *et al*. (1993) and Bartlett and Corell (2003). Underflow into the system occurs near Lake Pleasant, North Hassayampa, South Hassayampa, Santan-Sacaton, and Florence (Figure 2.6).

2.3.2 Natural Recharge

The natural recharge components are broken into four types: mountain front, stream infiltration, major drainage flood flow, and groundwater underflow. Mountain front recharge is distributed at the margins of alluvial basins along seven separate mountain ranges bordering the SRV study area (Figure 2.6). The mountain front volume estimates were originally derived from Thomsen and Porcello (1991) and later modified by Corell and Corkhill (1994). The value per mountain range represents a long term average due to annual variability of precipitation. The majority of the mountain ranges surrounding SRV are situated at lower elevations (maximum of 4,000 ft along Superstition Mountains), receiving less precipitation and contributing less recharge than mountain ranges at high elevations. As a result, mountain front recharge is a small component of the overall conceptual inflow.

Stream infiltration was estimated as a long term average for smaller ephemeral streams that flow into the SRV model area including New River, Skunk Creek, Cave Creek, and Queen Creek (Figure 2.6). Recharge from stream infiltration represents the intermittent flow occurring in a given year rather than large flood events. The recharge volumes per stream reach were estimated using stream flow records from the Maricopa Flood Control District stream gages. In addition to long-term average estimated ephemeral stream infiltration, sporadic recharge from gaged surface events on the significant ephemeral rivers and streams was estimated for the period 1988 to 2006. Between 1983 and 2006, flood flows occurred irregularly on six separate stream reaches (Salt River, Gila River, Queen Creek, Agua Fria River, Cave Creek, and Indian Bend Wash). Therefore floods represent the only natural recharge component that varies throughout time in the conceptual budget. The flood flow values were calculated using stream gage data or dam release rates. Flood flows occurred on at least one of the six stream reaches during all modeled years except 1990.

2.3.3 Incidental Recharge

Incidental recharge is defined as water that recharges the regional aquifer during the course of its use for agricultural, industrial, or municipal purposes. On average, incidental recharge is responsible for nearly 85% of the total estimated recharge into the groundwater system.

Agricultural recharge is the dominant recharge source to the SRV regional aquifer. Irrigated agricultural lands contribute to the regional aquifer when applied water percolates below the plant root zone rather than being utilized by consumptive use or evaporation. The delay in water percolation through the unsaturated zone is referred to as lagged agricultural recharge and is dependent on the depth to water (DTW) BLS and the unsaturated zone soil properties (unsaturated hydraulic conductivity, antecedent soil moisture, etc). Historical agricultural land coverage was used to conceptualize the spatial extent of agricultural lands and a lag factor for travel time through the unsaturated zone was estimated to be between 10 and 15 years based on the DTW and estimated percolation rates. Using the lag factor the water reaching the water table between 1983 and 2006 would be representative of the agricultural activity between 1968 and 1996. In areas where the depth to water is relatively shallow, such as Buckeye, the lag time is diminished. A USGS (1973) delineation of irrigated lands was used as the average spatial extent of the irrigated lands during the simulation period. In conjunction with the 1973 spatial extent, the location of Irrigation Grandfathered Rights (IGFRs) was used. Between 1983 (1968-1973) and 2006 (1991-1996) estimated agricultural recharge has diminished by approximately 300,000 ac-ft/yr.

Most urban recharge represents flood irrigation recharge applied to Salt River Project (SRP) urban irrigated lands. Turf recharge represents recharge applied to parks and golf courses. The amount of urban and turf recharge has remained constant over time with average values of 32,800 and 19,700 ac-ft/yr representing urban and turf recharge respectively. Artificial lake recharge was delineated from areas with golf course ponds and other artificial lakes. The lake recharge increased from 6,500 ac-ft/yr in 1983 to 13,600 ac-ft/yr in 2006.

Canal recharge occurs as a result of the water seeping through the bottom of canals. Canal recharge was divided into two categories: unlined and lined canal recharge. The unlined canals consisted of San Carlos Irrigation Project (SCIP) canals in the southern SRV area, the Buckeye Irrigation Canal, and the SRP grand canal that is unlined in some areas. The recharge losses through the SCIP canals is provided in the SCIP annual reports and based on total water received and field application volumes. It was assumed that by 1983 most non-SCIP canals were lined and transmitted uniform seepage per canal segment. Non-SCIP canals include the SRP system, Roosevelt Irrigation District (RID), Roosevelt Conservation Water District, the Central Arizona Project (CAP), and Maricopa Water District (Beardsley).

Treated wastewater (or effluent) recharges the regional aquifer in the channel of the Salt River below the points of discharge from the wastewater treatment plants (WWTP) at 23rd Avenue and 91st Avenue. Artificial recharge of other effluent sources and non-effluent recharge occurs at locations such as permitted underground storage facilities (USF). Artificial recharge has progressively increased since 1989. The values used within the conceptual budget are derived from the annual reporting values provided by the ADWR Recharge Program.

2.4 System Outflow

System outflows are defined as flow components within the SRV model area that remove water from the aquifer. Those components include underflow, pumpage, evapotranspiration, and groundwater discharge to stream channels (Figures 2.6 and 2.7).

2.4.1 Underflow

Groundwater underflow occurs in the regional aquifer at two locations; Maricopa-Stanfield and the Gila River. The Maricopa-Stanfield outflow is a result of pumpage in the Maricopa-Stanfield subbasin of the Pinal AMA. In that area agricultural pumpage has reversed the natural flow direction. Darcy strip analysis of water level gradients along the model boundary indicates that the flux out of the model averages 29,200 ac-ft/yr. A second source of underflow leaving the model area occurs along the Gila River, north of the Buckeye Hills, at a rate of 7,500 ac-ft/yr.

2.4.2 Pumpage

Annual pumpage volumes per well within the Phoenix AMA were obtained from the ADWR Registry of Grandfathered Rights (ROGR) database (Table1, Appendix A) and were then spatially clipped to the model domain. Pumpage within the model domain represents over 90 percent of the groundwater system’s total outflow between 1983 and 2006 based on the model domain conceptual budget. The total pumpage is dominated by agriculture; however, agricultural pumpage declined from 80 percent of total pumpage in 1984 to 48 percent in 2006. Municipal pumpage increased from 16 percent to 33 percent over the same period.

2.4.3 Evapotranspiration

Evapotranspiration (ET) is a result of phreatophyte growth, primarily along the Salt and Gila River riparian corridors. Phreatophyte growth was calculated using 1987 LANDSAT digital imagery and separated into five density type categories including bare, spare, medium, dense, and cropped lands (Corkhill *et al.* 1993). The density categories determine the rate of ET. In addition to density type, the ET rate was also controlled by depth to water. Estimates of ET along the Gila and Salt corridors decreased from 48,000 ac-ft/yr to 25,000 ac-ft/yr between 1983 and 2006 due to loss of riparian habitat and declines in the water level (Figure 2.6).

2.5 Conceptual Water Budget

Conceptual water budgets vary between 1983 and 2006 as a result of changes in flood flow, pumpage, canal seepage, artificial recharge, and agricultural recharge (Table 1). The estimated total inflows for the study period were approximately 23.6 million ac-ft. The total outflows were approximately 23.8 million ac-ft (Table 1, Appendix B). The estimated increase in the volume of groundwater storage was 2 million ac-ft. The change in volume is likely due to increased effluent and non-effluent recharge, decreased agricultural pumpage, and the use of different methods of calculation for agricultural and flood flow recharge over time.

Table 1: SRV Conceptual Water Budget Summary

Conceptual Inflows	1983-2006 Conceptual Range (Ac-Ft/Yr)
Underflow	31,800
Agricultural Recharge	350,000 – 775,000
Urban Recharge	32,800
Turf Recharge	19,700
Canal Seepage	71,000 – 196,000
Artificial Lake Recharge	6,500 – 14,000
Effluent Recharge	1,800 – 29,500
Flood Flow Recharge	0 – 1,016,000
Ephemeral Recharge	16,300
Mountain Front Recharge	16,300

Conceptual Outflows	1983-2006 Conceptual Range (Ac-Ft/Yr)
Underflow	36,700
Pumpage	618,000 – 1,320,000
Evapotranspiration	25,000 – 48,000

2.6 Estimates of Groundwater in Storage

Estimates of groundwater in storage for the SRV study area between 1983 and 2006 vary depending on assumptions regarding depth to bedrock, delineation of water levels, and aquifer specific yield values. Groundwater storage estimates developed between 1998 and 2003 range from approximately 68 million ac-ft to 71 million ac-ft. The estimate is based on groundwater storage in the model domain above the 100-year 1,000 foot BLS Assured and Adequate Water Supply (AAWS) regulatory depth limit within the Phoenix AMA.

3.0 Description of Numerical Groundwater Flow Model

3.1 Modeling Approach

The SRV regional groundwater flow model study area is approximately 5,578 mi^2 in size. As a result of geographic boundaries the active model domain is limited to approximately 2,505 mi^2 of the total study area (Figure 3.1). The model simulates transient (developed groundwater) flow conditions from 1983 to 2006. The transient period was divided into 24 annual stress periods between 1983 and 2006. Each stress period had a time step multiplier of 1 or 1.05. The model units of length and time are feet and days, respectively. The model was developed using the UTM Zone 12 North (NAD 1983 HARN) coordinate system. As discussed in Section 2.1, the regional aquifer was divided into three model layers to enable the model to simulate three-dimensional groundwater flow. The model simulates underflow into and out of the SRV, natural recharge from mountain front and stream channel infiltration, incidental recharge from agricultural irrigation and canal seepage, effluent release, evapotranspiration from riparian vegetation along the Salt and Gila Rivers, artificial recharge, and groundwater pumpage. The SFR package also simulates some groundwater discharge in the area of Salt and Gila River confluence. The model was based upon the conceptualization of the aquifer system presented in Section 2.0. The general characteristics of the SRV regional groundwater flow model are presented in Table 1. A detailed description of the model design is discussed below.

The model code selected to simulate groundwater flow in the SRV was the Modular Three-Dimensional Finite Difference Groundwater Flow Model, referred to as MODFLOW, developed by the U.S. Geological Survey (Harbaugh *et al.* 2000). The calibration of the transient model was accomplished using the MODFLOW 2000, version 1.18.

Table 2: SRV Model Components

Model Component	Description	Units
Transient Period	1983 – 2006	Time = Days, Length = Feet
Model Grid	125 Rows x 222 Columns	Model Cells = 0.5 mi^2
Model Origin (Lower Left)	UTM, Zone 12, HARN 1983, Feet	X = 977786.624016 Y = 11989576.0696
Model Cell Types	No Flow, Constant Head, Variable Head	
Boundary Conditions	Constant Head and Specified Flux	
DIS Package	Specifies aquifer tops and bottoms and time discretization	
BAS Package	Specifies starting water levels and active model domain	
Block-Centered Flow (BCF) – Rewetting Active	Specifies hydrologic parameters and allows rewetting of cells that go dry prior to or during a simulation	Rewetting Threshold = 20 Feet
Layer 1 – 9,420 active cells	Layer Type 1 – Unconfined Aquifer, T = K x Saturated Thickness	K = Feet / Day
Layer 2 – 9,370 active cells	Layer Type 3 – Confined / Unconfined Aquifer, T = K x Saturated Thickness	K = Feet / Day
Layer 3 – 9,370 active cells	Layer Type 3 – Confined / Unconfined Aquifer, T = K x Saturated Thickness	K = Feet / Day
Vertical Leakance	Assigned based on the areal distribution of percent fines in each layer and horizontal / vertical (K_H/K_V) ratio	1 / Days
Specific Yield	Volume of water yielded per unit area per unit change of water level in unconfined aquifer	Dimensionless
Storage Coefficient	Volume of water yielded per area per unit change in a confined aquifer's potentiometric surface	Dimensionless
Pumpage	Assigned to all simulated well locations	$Feet^3$ / Day
Recharge	Applied to specified uppermost active cells	Feet / Day
Evapotranspiration	Assigned rates per cell; Extinction Depth 20ft	Feet / Day
Stream Flow	Simulated groundwater flux between perennial stream reaches and aquifer	
Numerical Solver	Geometric Multigrid Solver (GMG)	Closure Criteria = 1 Foot

3.2 MODFLOW Packages

The SRV groundwater flow model utilizes ten packages and one numerical solver that are available in MODFLOW 2000. The packages are: Basic (BAS), Block-Centered Flow (BCF), Discretization (DIS), Well (WEL), Recharge (RCH), Stream (STR), Evapotranspiration (EVT), and the Time-Variant Specified-Head Package (CHD). The numerical solver utilized was the Geometric Multigrid Solver (GMG). The brief discussion below describes how each package was used in modeling the SRV regional aquifer.

1. The BASIC (**BAS**) package designates the active model domain and the starting water levels (1983) for each active cell. The package defines cells as no-flow, variable head, or constant head.

2. The Block-Centered Flow (**BCF**) package defines the cell-centered hydraulic parameters of the model. The hydraulic parameters defined in the BCF package are the cell-specific horizontal hydraulic conductivities or transmissivities, vertical conductance, and storage terms. The BCF also controls the rewetting option.

3. The Discretization (**DIS**) package establishes the physical layout of a model. The package assigns the number of model rows and columns, the number of model layers, the physical dimensions of each cell and the layer tops and bottoms. The DIS package also assigns the model time and length units and stress period number and length.

4. The Well (**WEL**) package is used to simulate water that is withdrawn from or added to a model, usually by a well. The well is assigned a specified rate for a given stress period and is located within the model based on a row and column designation.

5. The Recharge (**RCH**) package can be used to add aerially distributed water to selected cells within a model. Usually the recharge package is used to simulate precipitation that percolates into the aquifer, mountain-front recharge, or various incidental recharge sources.

6. The Stream Flow Routing (**SFR**) package simulates the routing of flow from rivers, streams, canals, or ditches as well as the leakage between the channel and the aquifer system. The interconnectivity of the stream channel with the aquifer is dependent on the water table elevation.

7. The Evapotranspiration (**ET**) package can be used to simulate groundwater outflow that is transpired by riparian vegetation or direct evaporation of groundwater at the land surface.

8. The Time-Variant Specified-Head (**CHD**) package is used to simulate time-varying specified heads. The package allows constant head cells to be assigned different values at different times during the model simulation, which allows boundary fluxes to vary through time based on the hydraulic gradient between the specified-head and variable heads within the model.

9. Hydraulic-Head Observation (**HOB**) option within the BAS package is used to compare simulated heads with observed water levels (heads). The HOB allows observed heads to be weighted based on their accuracy, and the resulting head residuals to be statistically evaluated. The HOB is a post-processing feature within MODFLOW.

10. Hydrograph program (**HYDMOD**) generates time-series data (i.e. hydrographs) from MODFLOW’s simulated heads at designated well locations within the SRV model domain. The HYDMOD is a post-processing feature within MODFLOW.

11. Numerical solvers are used by MODFLOW to solve the large system of linear finite-difference groundwater flow equations needed to calculate movement of water into and out of the model cells. The model solver, Geometric Multigrid (**GMG**) package, was used in the transient simulation.

3.3 Boundary Conditions

The incorporation of boundary conditions into the SRV groundwater model is critical in defining hydrologic conditions along the model borders. Three types of boundaries were applied to the SRV regional aquifer model: constant head, specified flux, and no-flow. Simulated fluxes across constant head boundaries were proportional to both the hydraulic gradient and the conductance between constant head cells and the adjacent variable head cells. A constant head boundary was used to simulate the underflow into the South Hassayampa area of the model, and underflow out of the model. Specified flux boundaries were used to simulate underflow out of the model at Maricopa-Stanfield and underflow in at New River / Lake Pleasant, North Hassayampa, Santan-Sacaton, and Florence (Table 3) (Figure 3.2). The inactive model cells simulate "no-flow" boundaries where groundwater flow into or out of the model does not occur. The calibrated values used for each boundary were within a similar range to those used in the Corell and Corkhill (1994) and Bartlett and Corell and (2003) studies.

Table 3: SRV Model Boundary Summary

Boundary Name	Boundary Type	Total Flux (Ac-Ft/Yr)	# Model Cells	MODFLOW Package
North Hassayampa	Specified Flux	5,000	56	WEL
South Hassayampa	Constant Head	12,000	22	CHB
Gila River	Constant Head	7,500	4	CHB
Maricopa-Stanfield	Specified Flux	29,200	58	WEL
Santan-Sacaton	Specified Flux	8,500	14	WEL
Florence	Specified Flux	3,800	34	WEL
Lake Pleasant / New River	Specified Flux	2,500	5	RCH

3.4 Model Data Development

The 1983 – 2006 SRV model update relied primarily on previous ADWR SRV model datasets (1994 – 2004) for the model's foundation. The earlier updates that were made utilized the ADWR Groundwater Site Inventory (GWSI) and ROGR databases, driller's logs, geophysical logs, and previous models developed for Assured and Adequate Water Supply and USF Recharge applications. A discussion of sources of data used to develop the ADWR model datasets is presented below.

3.4.1 Water Levels

Observation head data were used to establish water levels for the transient model's initial conditions and create calibration target water level maps. The initial water levels are critical because they serve as the starting point for the model simulation. The calibration target water level maps assist in evaluating model simulation of regional flow conditions.

Water level data for target water level maps and observation heads were obtained from the ADWR GWSI database. The development of the 1983 water level contours relied on previously developed ADWR water level contour maps for the UAU and MAU/LAU (Figures 3.3 and 3.4). The contour maps were re-evaluated by querying 1983 and 1984 water levels from the ADWR GWSI database. A total of 3,969 observation wells having perforation data were categorized into one of the three geologic units (UAU, MAU, LAU) based on the screened perforated interval. The re-evaluated water levels closely matched the previous ADWR contour maps with the exception of the Lake Pleasant region, where water levels had not previously been contoured. The water level contours representative of the 1983/1984 measured heads were extrapolated into a grid file using a kriging method. The grid was then used to assign each active model node a water level representative of initial 1983 conditions.

Water level data were acquired from the GWSI database for the SRV during years when basin-wide sweeps occurred, measuring the greatest number of wells. Maps were constructed for water level conditions in 1992-93 (1257 measurements), 1997-98 (1320 measurements), and 2002-03 (1547 measurements). The GWSI water levels for the sweep years were used to develop the Head Observation Package (HOB) to compare simulated heads for the same period. Further explanation of the HOB can be found in Section 4.3.

3.4.2 Aquifer Parameters

Aquifer parameters of hydraulic conductivity and storage values for this study remained relatively unchanged from the previous 2004 SRV model update. In the Lake Pleasant region, the estimated aquifer parameter values originated from the 2003 City of Peoria groundwater model (Bartlett and Corell, 2003) and were adjusted during the calibration process outlined in Section 4.0. Hydraulic conductivity for each model layer was re-calculated to account for modifications in model layer saturated thickness and consequently that were a result of updated geologic analysis. Further explanation of the K recalculation methodology is provided in Section 2.2. Figures 3.5, 3.6, and 3.7 illustrate the model calibrated K distribution per model layer. Storage values were basically unchanged from the previous ADWR model update (2004). Figures 3.8, 3.9, and 3.10 illustrate the modeled specific yield distribution per model layer. When fully saturated, the storage coefficient was used rather than specific yield. The storage coefficient for Layers 2 and 3 was set at 0.005.

The vertical conductance (VCONT) between layers 1 and 2 and layers 2 and 3 was simulated using the VCONT calculation. The $\mathrm{VCONT}_{1\text{-}2}$ and $\mathrm{VCONT}_{2\text{-}3}$ was calculated using the layers initial saturated thickness and vertical hydraulic conductivity as described in Equation1 for $\mathrm{VCONT}_{1\text{-}2}$.

$$\textit{Eq. 1} \quad Vcont_{1\text{-}2} = \frac{1}{\frac{(V_1)/2}{K_{v1}} + \frac{(V_2)/2}{K_{v2}}}$$

Where:
$\mathrm{VCONT}_{1\text{-}2}$: Vertical Leakance between Layers 1 and 2
V_1: Saturated Thickness of Layer 1 (feet)
V_2: Saturated Thickness of Layer 2 (feet)
K_1: Vertical Hydraulic Conductivity of Layer 1 (feet/day)
K_2: Vertical Hydraulic Conductivity of Layer 2 (feet/day)

The final calibrated ratios of horizontal hydraulic conductivity to vertical conductivity for Layers 1, 2, and 3 are listed below. The values have been changed from the 2004 SRV model to account for changes in model layer thickness and K values made during the model's geologic updates, particularly in Layer 2.

Layer 1 Horizontal - Vertical ratio: 10:1

Layer 2 Horizontal - Vertical ratio: 20:1

Layer 3 Horizontal - Vertical ratio: 12:1

3.4.3 Pumpage

Groundwater pumpage has remained the dominant outflow water budget component from the regional aquifer. The SRV model pumpage dataset was developed by querying the ADWR ROGR database for well specific pumping between 1984 and 2006. The 1983 pumpage dataset was interpolated using linear trend line analysis between reported 1975-1979 pumpage and the 1984 ROGR pumpage values. The pumpage was vertically distributed to model layers using three methods: 1) based on the perforated interval cited by GWSI, 2) based on well depth if perforation data was not available. It was assumed that the well was perforated over the entire well length, 3) based on average well depth in area.

The WEL package was used to simulate pumpage from each well per model layer based on the methods cited above. When necessary, simulated pumpage was set to deeper model layers to maintain simulated pumpage rates. During the transient simulation period, between 0.04 and 0.31% (Average 0.18%) of the total pumpage (ROGR and GRIC) was lost to dry cells. The greatest density of pumpage occurs throughout the agricultural lands of the west SRV (Figure 3.11).

3.4.4 Evapotranspiration

Evapotranspiration occurs along the Salt River and Gila River riparian zones as a result of phreatophyte growth (Figure 3.12). The ET package required three types of data: ET rate, extinction depth, and surface elevation. A total of 895 models cells simulate ET at various rates ranging from 2 to 782 ft/day. The rate used depends on the density and type of riparian vegetation as delineated in the original SRV model (Corkhill *et al.* 1993). The ET extinction depth was simulated at a constant 30. The ET surface elevation was calculated by selecting the cell center surface elevation from a 30-meter DEM, rather than using the elevation averaging technique as applied to land surface elevations for the discretization package.

3.4.5 Streamflow Routing and Groundwater / Surface-Water Interactions

Streamflow and groundwater / surfacewater interactions were simulated using the stream (STR) package developed by Prudic (1989). The stream package simulates flow in the major stream beds of SRV. The SRV stream network contains 461 model cells separated into twenty stream segments (Figure 3.13). The segments represent the remaining perennial or intermittent reaches of the Salt, Gila, Agua Fria, and Hassayampa River systems in the model area and the Buckeye Irrigation Canal Diversion. The stream package also serves as an input for flows from the 23rd and 91st Avenue WWTP Facilities and the Indian Bend Wash (IBW). The stream package simulates losing and gaining reaches throughout the stream network by simulating the difference in elevation between the stream stage and the water table during a given stress period. If the water table is above the stream stage, the reach is gaining and if below the stream stage the reach is losing.

3.4.6 Natural Recharge

Natural recharge was simulated through the MODFLOW RCH package. The RCH package simulated mountain front and recharge from flood flow.

Mountain front recharge was simulated along seven separate mountain fronts and the Lake Pleasant / New River inflow boundary with a constant annual rate per model cell (Figure 3.14). The initial mountain front recharge values applied to the model remained similar to conceptual model values derived from Corell and Corkhill (1994). Additional mountain front recharge was simulated along the White Tank, Sierra Estrella, and New River Mountain fronts. The total recharge applied to the model was 16,692 ac-ft/yr (Table 4).

Table 4: SRV Mountain Front Recharge Summary

Location	Mountain Front Recharge Flux (Ac-Ft/Yr)
White Tank Mountains	428
Sierra Estrella Mountains	844
New River Mountains	2,560
McDowell Mountains	1,599
Goldfield Mountains	904
Superstition Mountains	9,887
Usery Mountains	470

Recharge from ephemeral stream channel infiltration was simulated for sporadic flood flows or major drainages and typical long-term natural stream recharge on lesser ephemeral streams. Flood flow recharge was simulated on the Salt River, Gila River, IBW, Queen Creek, Agua Fria River, and Cave Creek and was lumped into an annual total per model cell in the RCH package (Figure 3.15). The flood flow volumes were decreased linearly downstream to reflect decreasing infiltration along the downstream stream length. In 1983 and 1993 major flood events produced approximately 40% of the total model recharge. A total of 15,115 ac-ft/yr of natural recharge was simulated along Queen Creek, Cave Creek, Skunk Creek, and New River. Similar to the flood flows, natural recharge decreased linearly along the downstream length.

3.4.7 Incidental Recharge

Incidental recharge was simulated through the MODFLOW RCH package. Incidental recharge is simulated from agricultural, industrial, and municipal sources.

Agricultural Recharge

Agricultural recharge is the dominant component of simulated recharge in the SRV basin. Conceptually, the impact of agricultural recharge to the aquifer is delayed due to vadose zone properties and thickness. The recharge applied through the MODFLOW recharge package does not directly account for vadose zone travel time. As a result of this MODFLOW code limitation, the agricultural recharge was lagged manually with lag times calculated based on depth to water. The average lag rate was estimated to occur at a rate of 20 feet per year (Corell and Corkhill, 1994). The actual lag rate may vary by area and therefore model simulated lag times include a level of uncertainty. With the exception of one USF recharge site, agriculture was the only recharge component that was lagged.

The greatest rate of agricultural recharge was simulated in the West SRV, Buckeye corridor, and in the southeast SRV near Queen Creek (Figure 3.16). The geographical distribution and volume of agricultural recharge decreased during the transient period from 745,000 ac-ft/yr in 1983 to 611,000 ac-ft/yr in 2006. Fluctuations of the trend during the 23 year period are likely a result of urbanization and agricultural practices.

Artificial Recharge

Artificial recharge, of effluent and water from other sources, was simulated at 29 facilities throughout the SRV (Figure 3.17). The number of model cells simulating the annual recharge per facility was based on the annual volume being recharged and the size of the facility. For example, GRUSP recharge volume was distributed among 14 cells to help reduce mathematical instability in the model and match the size of the facility. A total of 96 model cells were used to represent the 29 sites during the transient period. The volumes applied per year were provided by the ADWR Recharge Program. The Hieroglyphic USF (NW SRV) was the only facility which artificial recharge was phased (10% first year, 20% second year, 30% third year, 20% fourth year, and 10% the 5th year). The phased approach simulated a pulse effect that more appropriately represented conditions. Discharge from the two primary WWTP facilities, the 23rd and 91st Avenue WWTPs, was simulated using the stream routing package rather than the recharge package.

Canal Recharge

Canal recharge was simulated using two categories of canals: SCIP Canals and CAP and non-SCIP canals (Figure 3.18). The amount of recharge per canal segment was based on the canal category. The SCIP canals in the southern SRV are unlined and apply a constant recharge rate of 0.05 ft^3. The SCIP canals are not based on the wetted surface area. The non-SCIP and CAP canals were assigned a recharge rate of 0.05 $ft^3/day/ft^2$ of wetted canal area.

A total of 191 model cells simulated 4,230 ac-ft/yr of recharge along the CAP canal. The SCIP canals used a total of 163 cells to simulate between 10,000 and 41,000 ac-ft/yr during the transient simulation. The non-SCIP canals simulated 54,925 ac-ft/yr of recharge through 828 model cells.

Lake Recharge

The simulation of lake recharge represents artificial lakes (typically on golf courses) greater than 10 acres. A total of 210 cells simulated between 6,535 and 13,580 ac-ft/yr during the transient period (Figure 3.19). The increased recharge volume over time is indicative of the growing number of artificial lakes during the period.

Turf / Urban

The simulation of turf and urban recharge represented golf courses, parks, and other areas to which urban flood irrigation was applied. Due to the limited nature and quantity, residential urban recharge was not considered. The rate of urban / turf recharge applied remained constant through the transient model simulation. A total of 871 cells simulated 32,746 ac-ft/yr of urban recharge between 1983 and 2006 (Figure 3.20) and a total of 603 cells simulated 19,419 ac-ft/yr of turf recharge (Figure 3.21).

4.0 Calibration

4.1 Model Calibration Process

Model calibration generally involves varying model inputs within acceptable real-world ranges to obtain a realistic match between model-simulated data and field-observed or estimated data. The purpose of the calibration process is to minimize the difference, or error, between model simulated output and observed data; yet still maintain a set of hydrogeologic input data that is consistent with independent estimates or observed data. Because the SRV update model utilized much of the previous model's hydrologic data inputs, many cell-centered model inputs were unchanged from the previous model. Agricultural recharge was the input most highly modified during model calibration; hydraulic conductivity, mountain front recharge, and canal recharge were other inputs that were also adjusted to varying degrees.

4.2 Calibration Criteria and Model Error

Anderson and Woessner (1992) recommend establishing calibration criteria prior to model calibration as a means for evaluating individual model simulations. The calibration criteria consists of observed or estimated data that are compared to model simulated data to judge when a model simulation adequately replicates the flow system being modeled. The calibration criteria should include individual calibration targets and more generalized systemic targets. Individual calibration targets can include water levels or estimated fluxes that have a measured or estimated value and an associated acceptable calibration tolerance (or error). More generalized targets can consist of localized or regional water budget estimates that can have wider acceptance tolerances. Using the calibration targets and their associated error as guidelines, calibration levels can be defined for each calibration target. The calibration levels can then be used to define the point at which a simulation's error is minimized and the model can be regarded as being adequately calibrated.

Anderson and Woessner (1992) also discuss several common statistical-based measures used to evaluate model error. The measures use model head residuals, the difference between simulated and observed heads, to describe the overall model error. The measures include the mean of the head residuals, the mean of the absolute value of the head residuals, and the standard deviation (also called the root mean squared error (RMSE)) of the residuals.

The mean of the head residuals describes the mean error (ME) of a simulation and indicates whether the model is over or under simulating heads. That is, are the simulated heads consistently above or below observed heads? The closer the ME is to zero the better. A very small ME indicates that there are about as many positive residuals as negative residuals. An even more useful measure of model error is the mean of the absolute value of the head residuals, also called the absolute mean error (AME). Because the AME uses the absolute values of the head residuals, it indicates how close model simulated heads are to observed heads and as such, better measures overall model error than the ME. The model calibration process should attempt to minimize the value of the ME and the AME. Another useful measure of model error is the ratio of the RMSE to the total head loss in the system being modeled. The RMSE is a measure of the spread of the residuals about the mean (Helsel and Hirsch, 2002), and is calculated by dividing the RMSE of the head residuals by the total head loss across the system being modeled. If this value is low (less than 10 percent is a generally accepted threshold) then the model error is considered to represent only a small part of the overall model response (Anderson and Woessner, 1992). See Anderson and Woessner (1992) Chapter 8, for a detailed discussion on evaluation of a model calibration.

The statistical methods described above give an indication of the average error of a model simulation. However, it is also important to examine the spatial distribution of model error to determine if there are areas in the model with excessive error. The occurrence of spatial bias in the model error indicates problem areas in the model, which can then be addressed during the calibration process. There are several methods that can be used to look for spatial bias in a model simulation. Plotting residuals from each simulation on a map, constructing scatter plots of the observed vs. simulated head pairs, and plotting residuals vs. observed heads can all be used to check for spatial bias trends.

Based on previous modeling experience and suggested model error criteria from Anderson and Woessner (1992) the following calibration criteria were developed for the SRV model. The residual weighting is based on altitude accuracy of the well as documented by GWSI. The percentage criteria were determined through the analysis of previous modeling studies.

- The total head change across the SRV model is approximately 1,020 feet. All weighted model residuals will be less than or equal to 10 percent of the total head change, or 102 feet.
- The weighted ME residual will be less than 1 percent of the total head change, or ± 10 feet.
- The mean of the absolute value of the weighted head residuals will be less than 2 percent of the total head change, or 20 feet.
- 95 percent of the absolute value of the weighted head residuals will be less than or equal to 5 percent of the total head change, or 50 feet.
- The RMSE of the weighted head residuals will be less than or equal to 2 percent of the total head change, or 20 feet.
- The ratio of the head change to the RMSE will be less than 10 percent.

More generalized model calibration criteria include water budget data and regional water levels trends generated by the simulation. These calibration criteria are subjective measures of model validity because of the uncertainty involved in how they were determined or how the results are interpreted.

The model simulated water budget components should generally be within the range of conceptual estimates that were used as initial starting points. Percentage ranges can be assigned to some water budget components where there is less uncertainty. In most areas the model simulation should be able to replicate the general trends in historic water levels. Hydrographs will be created that compare observed water levels to model simulated heads that are generated by MODFLOW's HYDMOD.

4.3 Calibration Targets

Water level data and the conceptual water-budget components were used to establish calibration targets for this study. The water-level calibration targets were established as 10 percent of the head drop across the model, which is 1,020 feet. That resulted in setting calibration levels in multiples of plus or minus 10 feet as listed below:

Level 1 – simulated water level within ± 10 feet of observed water level
Level 2 – simulated water level within ± 20 feet of observed water level
Level 3 – simulated water level within ± 30 feet of observed water level
Level 4 – simulated water level within ± 40 feet of observed water level
…
Level N – simulated water level within ± (N * 10) feet of observed water level.

The water-budget calibration targets were set as having the conceptual water-budget component within the range of published estimates (Table 1).

The Hydraulic-Head Observation (HOB) option of the BASIC package was utilized to compare simulated heads with observed water levels (heads). The HOB option provided several important functions that include: 1) a weighting option that allows water-level observations deemed more accurate to be assigned more significance, or weight, than observations that are believed to be less accurate, 2) the ability to interpolate simulated heads from cell-centers to the location of observed heads, and 3) using model head residuals to calculate the basic statistical measures that describe how well the model results compare to expected normal distribution results. If the weighting option is used in the HOB process then the statistical measures are calculated using the weighted head residuals.

The observed head weighting method suggested by Hill (1998), which evaluates the accuracy of the observation point's altitude error, was utilized to determine the weighting factor for observed water levels. The average accuracy of an observation point's altitude can be determined using the assigned altitude accuracy for the observation point. The GWSI site altitude accuracy value was used to calculate the estimated standard deviation of a water-level elevation measurement error for each observation point after Hill (1998). The resulting weighting factors ranged from 0.033, for observation points with very inaccurate altitudes, to 1.0, for observation points with very accurate altitudes. For an explanation of the head weighting procedure and a more detailed discussion of weighting observed data see Hill (1998).

The weighted residuals from the HOB package were used in the statistical and frequency distribution analysis that are presented in Appendix C. The weighted residual (difference) between model simulated heads and observed heads was determined using the formula:

$$R_i = H_s - H_m$$

Where:
R_i = the residual, in feet
H_s = the interpolated weighted model simulated head value at the location where H_i was observed, in feet
H_m = the weighted observed head at point *i*, in feet

This results in a positive residual if the simulated head is higher than the observed head and a negative residual if the simulated head is lower than the observed head. The head residuals form the basis of many of the calibration criteria. See Hill (1998) for a detailed discussion of issues related to parameter weighting and implementation of the Head Observation Processes in MODFLOW 2000.

4.4 Transient Calibration

Because the previous model's distribution of transmissivity was generally believed to be reasonable, the majority of changes to model input parameters during the transient calibration involved researching and adjusting agricultural recharge values. Except for years when there were major floods on the Salt and Gila Rivers, agricultural recharge was the largest component of the water budget, and therefore, has the largest impact on model results. The model transmissivity distribution was generally not adjusted except in the Lake Pleasant area, and in the very northwestern section of the model adjacent to the Hassayampa subbasin. The model layer geometry in the northwestern area was modified from the previous model, so some adjustment in cell-specific hydraulic conductivity values was necessary to achieve acceptable model residuals.

4.4.1 Calibration - Agricultural Recharge

Agricultural recharge is generally the largest component of water budget inflow, averaging 53 percent of total model inflows throughout the model simulation. In non-flood years agricultural recharge accounted for up to 75 percent of total model water budget inflows. Because agricultural recharge dominates the water budget and the annual volume has a great deal of uncertainty, adjusting agricultural recharge became the major device for the transient calibration.

The model was divided into sub-areas based on irrigation districts. The model head residuals and hydrographs that compared observed and simulated heads were used to determine which stress periods required modification of agricultural recharge. The recharge values in the sub-area were then increased or decreased by increments of 5 percent up to a maximum of 25 percent. After each recharge modification a new recharge package was created, the model was re-run, and the effect of the modifications on the heads and simulated hydrographs examined. A sub-area was considered calibrated when the head residuals were minimized and the hydrographs of the simulated heads reasonably match the observed hydrographs.

4.4.2 Calibration - Other Recharge Sources

Persistent over-simulation of water levels in the GRIC was addressed by adjusting Gila River flood flow recharge, agricultural recharge, and SCIP canal recharge. Many of the observed water level targets in the GRIC area were obtained from wells located along or very close to the SCIP canal system. These targets were very sensitive to adjustments in the volume of recharge assigned to the SCIP canal system. Initial values of SCIP canal recharge were developed using estimated annual volumes of canal loss as reported in the SCIP Annual Reports. Using these estimates as a starting point the annual SCIP canal recharge was increased or decreased such that head residuals were minimized and simulated hydrographs reasonably matched hydrographs of observed water levels.

4.4.3 Hydraulic Conductivity Modifications

As discussed in Section 2.2, model K values were recalculated using the 2004 SRV model's T distribution and the updated model layer geometry. In some instances the resulting cell-specific K values for a layer were unreasonably high or low. This was caused by changes in a cell's layer top or bottom elevations during the geology update. The model's initial transient calibration criteria used the recalculated K values with no modifications. Once the model's transient calibration criteria were met, the model layer K arrays were re-examined and, where appropriate, layer K values were modified to reflect K values of surrounding cells. Any change in total cell T was redistributed to other saturated layers within the vertical stack of model layers for a given model row and column, such that the previous model's transmissivity distribution was honored. A new BCF package was created and a model simulation was run with the revised K distributions. A comparison of model water budgets and model error statistics for the two simulations showed virtually no differences using the two different K distributions. The BCF package included in the model input files contains the revised K distribution.

The only area in the model where the K arrays were systematically modified as part of the transient calibration was the Lake Pleasant subbasin, which was added to the updated model domain. The initial K distribution for the Lake Pleasant area was taken from a model developed by Clear Creek and Associates (Bartlett and Corell, 2003). Boundary inflows from New River and mountain-front recharge for the New River Mtns. were modified along with layer K values during the calibration of the Lake Pleasant subbasin.

4.4.3 Model Solver Modifications

Initial attempts to run the updated SRV model using the PCG solver had convergence issues with cyclic wet/dry problems in many cells. Loosening the PCG's head closure criteria allowed the model to complete more stress periods, but the model still failed to converge and produced unacceptably large cumulative water budget error. Therefore, it was decided to use the USGS GMG solver to see if it could produce a model solution that converged with an acceptable cumulative water budget error. Documentation of the GMG solver indicates that the head and flux closure criteria in the GMG solver, while important in controlling model error, aren't directly analogous to the PCG solver's closure criteria.

The initial test simulations using the GMG solver using a head closure criteria of 5 feet and a residual flow closure of 100 ft^3 per day produced a model solution that converged with a cumulative water budget error of 0.02 percent. As calibration continued and the model became more stable the head and flow closure criteria were gradually reduced to 0.01 ft and 0.01 ft^3 per day, respectively. The PCG solver was reintroduced into the model as it became more stable. Using the PCG solver with a head closure of 0.01 ft and a flow closure of 864 ft^3 per day produced a model solution that converged with an acceptable cumulative water budget error. The final calibration data input sets will produce model convergence with a cumulative model water budget error of 0.00 percent.

4.5 Transient Model Results

The final transient calibration run was analyzed both quantitatively and qualitatively to determine the acceptability of the simulation to the established calibration criteria. Section 4.5 compares the simulated outputs to observed or conceptual values through water levels, hydrographs, the water budget, and zone budget analysis. The transient calibration met the selected calibration criteria outlined in Section 4.2.

4.5.1 Water Levels

The ADWR monitors water levels annually within the SRV, and approximately every five years a basin-wide water level sweep (i.e. measuring all wells basin-wide) is conducted for every accessible well in SRV. The re-occurring water level sweeps provide the most comprehensive evaluation of the regional aquifer. The sweeps occur during the winter months (October – March) to avoid impacts due to pumpage. During the transient calibration period three sweeps occurred; 1991-92, 1997-98, and 2002-03. The water level data from the three sweeps served as the quantitative and qualitative basis of water level calibration.

Water level contour maps were used to qualitatively evaluate model simulated heads. The ADWR developed three separate hand contoured water levels maps representing conditions during the 1991-92, 1997-98, and 2002-03 sweeps which were published as Hydrologic Map Series (HMS) Reports (Hammett and Herther, 1995) (Rascona, 2005). Within those years there were 1,381, 1,471, and 1,323 measured water levels used to contour observed and simulated head elevations, respectively. A water level contour map of the 2002 simulated water levels was superimposed over the hand-contoured map of 2002-2003 observed water level contours and presented in Figure 4.1(Rascona, 2005). The figure indicates that the model simulated regional trends that were consistent with observed water levels; however, localized discrepancies exist between the contours. This trend in simulated water level contours was consistent with each sweep year.

To quantitatively evaluate the water levels, well specific data from each of the three sweep years was compared to the simulated heads derived from the HOB package. The results were analyzed temporally (per sweep year) and spatially (East and West SRV subbasin).

The residual statistics for all sweep years indicate a general improvement in calibration during the transient calibration. The correlation coefficient for all weighted observed vs. simulated heads was 0.99 and included 4,175 wells between the three sweep years. The ME of all the weighted residuals was -0.20 feet and the AME was 11.3 feet for all sweep year's weighted residuals. Analysis of each sweep indicated residual error closely matching that of the total residuals for all three years. A statistical summary of the model residuals is presented in Table 5 and a complete list of residuals is provided in Appendix C.

The weighted residuals are evenly distributed between positive (47.2%) and negative (52.8%) values. However, several spatial trends in the data are evident from examining data in Figure 4.2. A spatial evaluation of residuals for the 2002-03 sweep year indicates several areas of less acceptable calibration including the West SRV subbasin and the central Phoenix corridor. A similar trend was noted for the 1991-92 and 1997-98 weighted residuals when plotted. The over simulation of water levels in the West SRV may be a result of USF impacts and their associated recharge not being properly simulated and/or the impacts of residual impacts f aquifer system compaction that was not simulated in the current model update. The under simulation of water levels through the Phoenix corridor may be due to insufficient historic agricultural recharge being applied to the system; however, the applied recharge was maximized based on the available historic information. The southeast SRV area had large positive and negative residuals along the Superstition Mountains, likely due to the limited water level data available to properly estimate the spatial distribution of hydraulic heads in that area.

Table 5: SRV Model Update Weighted Head Residual Summary

Model-Wide Head Residuals (Feet)						
Sweep Year	*ME*	*AME*	*RMSE*	*Range*	*RMSE Ratio*	*Count*
All Years	-0.2	11.3	17.5	-111 to 156	1.7	4175
1991-92	-0.3	11.0	17.2	-102 to 112	1.7	1381
1997-98	-0.3	12.1	18.9	-105 to 156	1.8	1471
2002-03	0.0	10.7	16.2	-111 to 94	1.6	1323
East SRV Subbasin Head Residuals (Feet)						
Sweep Year	*ME*	*AME*	*RMSE*	*Range*	*RMSE Ratio*	*Count*
All Years	1.6	10.2	15.8	-111 to 112	1.7	1840
1991-92	2.8	11.7	18.3	-102 to 112	2.0	595
1997-98	1.1	9.7	14.9	-105 to 77	1.6	654
2002-03	1.0	9.2	13.9	-111 to 79	1.5	591
West SRV Subbasin Head Residuals (Feet)						
Sweep Year	*ME*	*AME*	*RMSE*	*Range*	*RMSE Ratio*	*Count*
All Years	-1.6	12.2	18.7	-77 to 156	2.0	2300
1991-92	-2.6	10.5	16.0	-65 to 89	1.7	774
1997-98	-1.4	14.1	21.5	-77 to 156	2.3	807
2002-03	-0.8	11.9	17.9	-66 to 94	1.9	719

4.5.2 Hydrographs

Another method of evaluating the transient model simulation is to examine its ability to replicate transient aquifer response by comparing hydrographs of observed water levels versus simulated water levels. Hydrographs of 46 wells representing the most comprehensive water level records and a locator map are presented in Appendix D. The hydrographs were developed using the HYD package and are organized by region for ease of analysis. Discrepancies per hydrograph are qualitatively defined as hydrographs in which the long-term simulated trend deviates from the measured or the long-term residual error is large (>50 feet). In general, the simulated hydrographs closely replicate the measured declines and recoveries between 1983 and 2006. Discrepancies were noticeable within areas of the West SRV and North Scottsdale.

Hydrographs within the West SRV (Hydrographs 4, 5, 7, 12, and 16) indicate long term residuals to be greater than 50 feet through the majority of the transient simulation, possibly due to discrepancies in initial conditions. The majority of hydrographs reflect an under simulation of the water level elevation. The West SRV model error may be due to inaccurate simulation of agricultural and artificial recharge within specific areas. Observed water levels were also difficult to simulate within the North Scottsdale area (Hydrographs 22, 24, 25). The inability to accurately simulate water levels in North Scottsdale may be a result of vertical gradients between the UAU/MAU and MAU/LAU (City of Scottsdale, 2003).

4.5.3 Water Budget

The simulated water budget and each of its components were evaluated relative to the conceptual water budget (Appendix B). The conceptual versus simulated net water budget (Inflow – Outflow) varies in total volume; however, the trend between the two budgets is very similar. Variations in the simulated volumes are likely a result of calibration and model simulated interactions between ground and surfacewater.

Evaluation of the surfacewater – groundwater interaction was important to determine which sections of the stream were losing or gaining water from the aquifer into the primary stream reaches (Salt River, Gila River, Agua Fria River, Buckeye Canal and Hassayampa River). Flood flow can be an important component of recharge to the aquifer system. Figures 4.3 and 4.4 illustrate which reaches are contributing water to the stream and which reaches are losing water to the aquifer during two climatic extremes. Figure 4.3 represents conditions during a flood year (1993) and Figure 4.4 represents conditions during a drought year (2000).

4.5.4 Zone Budget

Subregional groundwater flows within the SRV active model area were calculated from MODFLOW output water budgets using the Zone Budget (ZONBUD) 3.0 program (Harbaugh, 2008). MODFLOW calculates flow between adjacent cells within the model domain, but only calculates cumulative water budgets tabulating flow into and out of the entire model domain. In order to calibrate large regional simulations containing multiple groundwater subbasins, it is useful to examine flux between subbasins using the ZONBUD program.

The model domain is delineated into subregions by assigning a zone number to each cell in the model domain (Harbaugh, 1990). GIS software was used to create a spatial database containing the flux zone distribution information, from which the ZONEBUD array file was built. The SRV model domain was divided into the following zones: East SRV subzone, West SRV subzone, the Scottsdale subzone, and the Lake Pleasant subzone (Figure 4.5). The zone distribution allowed for the examination of flows through critical areas, often the boundaries between delineated groundwater subbasins. Many of these boundaries of interest in the SRV also correspond to gaps between mountain ranges, through which the Valley's major rivers flow. A total of eight individual flux boundaries of interest were examined including the Gila, Papago, and Agua Fria Boundaries and are indentified in Figure 4.5.

The zone budget analysis reveals a model functioning largely within conceptual expectations. Simulated flow generally proceeds from east to west, as would be expected from the regional gradient. The annualized fluxes across the eight boundaries are detailed in Appendix E.

Flux through the Papago Boundary (1) migrates westward at an average rate of 786 acre-ft/yr in 1983, and 3,216 acre-ft/yr in 2006; the Gila Boundary (2) fluxes for the same years are 3,665 and 6,041 acre-ft/yr, respectively, in a northwesterly direction. An analysis of total flow between the West and East SRV indicated a net westward flux of 4,451 acre-ft/yr from East to West SRV in 1983, and 9,257 acre-ft/yr in 2006.

Groundwater flow from the Lake Pleasant subbasin remains relatively unchanged over the course of the simulation, owing to the sparse development that occurs in most of the subbasin. The regional gradient moves water south from Lake Pleasant into the West SRV (Boundaries 3, 4, 7), as well as southeast into Scottsdale (Boundaries 5, 6). Flux from Lake Pleasant to Scottsdale declines slightly from 1,445 to 909 acre-ft/yr between 1983 and 2006, while flux south into the West SRV is 8,850 acre-ft/yr until the Agua Fria Recharge Project increases the rate to approximately 14,000 acre-ft/yr near simulation's end.

One of the notable results of the ZONBUD analysis concerns flux between Paradise Valley and the East SRV (Boundary #8). Groundwater flows south here at a rate of 21,334 acre-ft/yr in 1983, and then steadily decreases until 1993. By 1994 the flow has reversed direction and the northward flow increases to 5,696 acre-ft/yr by 2006. The approximate 27,000 acre-ft/yr net reversal is indicative of the rapid development experienced in the portion of Scottsdale north of Boundary #8 during the simulation's timeframe.

5.0 Model Summary and Recommendations

Model Application

The primary objective of the SRV model update was to develop a numerical groundwater model capable of evaluating relative changes within the regional system. In conjunction with the model, the effort accumulated and organized hydrologic, geologic, and water use data into a readily available spatial database. The ADWR can use the model to apply different planning scenarios for assessment of long-term aquifer impacts.

Numerical groundwater flow models are useful tools to determine how an aquifer responds to changing stresses over time. ADWR's regional groundwater flow models, such as the SRV model, are among the best tools available for regional and sub-regional hydrogeologic analysis. However, regional models are, by their nature, only approximations of the natural flow system and represent averaged conditions over a large area based on known data. Large-scale regional models, such as models designed by the ADWR, may not be suitable for site-specific locations. This is especially true for model areas that relied on few to no data (Figure 2.5) or are along the model edges where boundary conditions and hardrock can impact the model results. Cell-size limitation, the lack of localized data, and the regional scale of the analysis make it difficult for the model to accurately simulate localized conditions.

Each ADWR regional model has known limitations and it can't be assumed that the models can be used as is without first reviewing the accuracy of the model calibration in the area of interest, appropriateness of model cell size, correspondence of model geologic structure and aquifer parameters with known field data, appropriateness of boundary conditions, etc. In many cases, the ADWR models may be sufficient to use as is. It is contingent on the user to review the model for their specific purpose and address any issues before the model can be used in support of the ADWR recharge program, AAWS program, or well impact analysis requirements. If an ADWR model is to be used in support of an ADWR program, the regional model should be reviewed for suitability before proceeding with the analyses.

Model Results

The results of the SRV model transient calibration indicate that the model acceptably simulates the groundwater flow system. Evaluation of long-term hydrographs and residual error during the three basin sweep years confirms the model’s ability to reproduce historic water level change. The model has a very low overall model error of 1.7 percent RMSE to head loss ratio and an average AME of 11.3 ft. In addition, the simulated model water budget closely matches conceptual estimates.

Model Recommendations

The update of the SRV model revealed potential modifications that may help improve the model simulation and identify model uncertainty. The following is a list of improvements that the ADWR is considering for the future SRV model updates.

1. Development of a 1900 steady-state model to simulate initial conditions.
2. Simulation of transient conditions from 1901-2008.
3. Application of a parameter estimation program, such as PEST, to evaluate correlation, sensitivity between parameters, and model uncertainty.
4. Defining the spatial extent of agricultural recharge during known time intervals within SRV. Agricultural recharge is a primary recharge component, so defining the extent and historic water application rates are critical to proper conceptualization.
5. Incorporation of subsidence into the transient simulation
6. Addition of Hassayampa subbasin to the model domain to prevent boundary conditions from impacting model results in the West SRV.

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FIGURES

APPENDIX A

Phoenix AMA Pumpage Summary (1984-2006)

APPENDIX B

Conceptual Inflow and Outflow (1983-2006)

APPENDIX C

Transient Calibration Statistics

APPENDIX D

Simulated vs. Observed Hydrographs

APPENDIX E

Annualized Simulated Zone Budget (1983-2006)